Site - Specific Probabilistic Seismic Hazard Analysis (PSHA) for THAL DOAB Area

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Copyright Statement

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All praises are due to almighty ALLAH, the most beneficent, the most merciful who gave me the strength to finish this work. My humble respects are to the Holy Last Prophet (Peace Be Upon Him) who emphasized to seek knowledge for the betterment of oneself and humanity.

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This Work is

Dedicated to my beloved parents and family,

Their continuous support and prayers led me to this delightful accomplishment.

Abstract

Pakistan lies in important geotectonic position and has seismically active zones in north and south. Seismic hazard analysis (SHA) entails the estimation of potential ground motion parameters at a specific region/site. The evaluations through seismic hazard analysis consider all historical and instrumental recorded seismicity and the possible sources of seismic activity to generate ground motion parameters probability of exceedance. SHA is performed through two main approaches to define seismic ground motion for structural design purposes e.g., deterministic & probabilistic seismic hazard Analysis. Ground motion parameters such as Peak Ground Accelerations (PGA) etc. are determined with annual probability of exceedance in a time interval for a specific location. Site specific probabilistic seismic hazard assessment (PSHA) for THAL DOAB area located in Punjab Plain is performed due to absence and lack of reliable site specific seismic hazard study. There are great prospects for industrial developments under CPEC in the region. The main objectives of this research are to perform a comprehensive site specific probabilistic seismic hazard study considering the site, soil conditions, near regional and regional tectonic settings and by developing seismotectonic model and earthquake catalogue. Finally, site specific peak ground accelerations have been derived taking into account the site response analysis for design of structures.

Key Words: *seismic hazard, earthquake catalogue, peak ground acceleration, site response*

ACRONYMS AND ABBREVIATIONS

SHA	Seismic Hazard Analysis
PSHA	Probabilistic Seismic Hazard Analysis
DSHA	Deterministic Seismic Hazard Analysis
PGA	Peak Ground Acceleration
ISC	International Seismic Center
USGS	United States Geological Survey
PMD	Pakistan Meteorological Department
NESPAK	National Engineering Services of Pakistan
MCE	Maximum Credible Earthquake
MDE	Maximum Design Earthquake
CPEC	China Pakistan Economic Corridor
UHS	Uniform Hazard Spectra
NGA	Next Generation of Ground-Motion Attenuation Models
NEHRP	National Earthquake Hazards Reduction Program
PEER	Pacific Earthquake Engineering Research Center

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CHAPTER 1

1. INTRODUCTION

Earthquakes are the main external hazards and significantly contribute towards any possible damage to existing and new structures planned to be built. The recent increase in seismic activity, developments in technological grounds and innovative civil structures required more emphasis on detailed seismic hazard analysis for a specific region against potential seismic forces. The civil structures performance depends a lot on design peak ground acceleration established for potential earthquake. The calculation of design ground motion parameters is a valuable process. These ground motions are presented on compatible hazard maps and in shape of response spectra. This research is focused to study the site specific earthquake ground motions to achieve the sustainable development in Thal Doab area.

Siting for a capital intensive development project is preliminary and one of the most important stages in assuring life time safety. The site area is evaluated against potential earthquake hazards. To establish the seismic hazard level for a specific area, the seismic zones around should be fully identified and characterized for predictive respective strong ground motions. Identification of seismic sources needs understanding of regional and local tectonic settings. As the effects of earthquakes may differ from region to region due to varying tectonic settings and site soil conditions, therefore, each region should have the relevant set of attenuation models for evaluation of seismic hazards in line with the international practices which are being followed. Seismic hazard for a particular site is normally established through a technique called seismic hazard analysis (SHA).

SHA is normally performed through two main approaches known as deterministic and probabilistic seismic hazard analysis to define seismic ground motion parameters in a specific region for structural design and analysis purpose.

1.1. Problem Statement

Pakistan lies in important geotectonic position and has seismically active zones in north and south. Due to uncertain and probabilistic nature of external hazards especially earthquakes, it is realized that this hazard should also be assessed probabilistically as well as deterministically. It is quite evident from the current global trend, international practices & guidelines and especially after Fukushima accident that PSHA should be conducted to ensure adequacy of existing design and to design new installations. International organizations suggested conducting PSHA studies to define seismic design levels for high risk installations.

There are great prospects for industrial developments under CPEC in the Thal Doab Area. In this regard, there is an urgent need to develop a site specific seismic source characterization model using the seismo-tectonic database. Site specific probabilistic seismic hazard analysis for Thal Doab in Punjab Plain area is performed due to absence and lack of reliable site specific seismic hazard study.

1.2. Research Objectives

The main objective of this research is to conduct a comprehensive site specific probabilistic seismic hazard analysis for THAL DOAB area located in Punjab to assess the seismic hazard. The soil conditions and regional seismotectonic data was utilized by latest software's i.e., HAZ45, Ez-FRISK and DEEPSOIL. Specific objectives of the research are:

a) To conduct a comprehensive PSHA for THAL DOAB Area

b) To develop earthquake catalogue & seismotectonic model for 280,000Km2 area

c) To determine the peak ground acceleration, PGA value at bed rock and surface

d) To incorporate the site response to define potential ground motion parameters in free field conditions.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Probabilistic Seismic Hazard Assessment

Traditionally, the seismic hazard analysis is utilized to estimate and establish the design ground motion parameters in a region of study by considering the all available records and relevant databases on seismicity, seismic activity, tectonic settings, geological evidence, soil conditions and development/selection of respective attenuation model for the region. The probabilistic computation estimates the expected ground motions for different annual probability of exceedance.

The model to consider the exceeding different values of ground motion at region for earthquake activity normally adopts a Poisson process. The probability with which ground motion parameters are exceeded in terms of temporal distribution is thus expressed as:

$$P(Z > z) = 1 - e^{-v(z)} \tag{1}$$

Where, ν(z) is the mean seismic activity exceeded per time interval

2.2 Background on Seismicity

The region around Pakistan has a high frequency of seismic activity. The seismic data for the region prior to 1905 is limited. The instrumental data is available after 1905. The historical record is based on intensity of earthquakes. The intensity in a region mainly depends on distance of the epicenter, the nature of soil, and the layout of the structures with respect to the seismic wave origin direction.

Analysis of the seismicity in THAL DOAB region depicts that most seismic activity is concentrated in the Suleiman Thrust Range, Chaman Fault, the Hindu-Kush Region and the main Himalayan thrust belt, with relatively minor seismicity associated with the stable portion of the Indian sub-continent. The Punjab Plain Province, in which the site is located, is a more stable area.

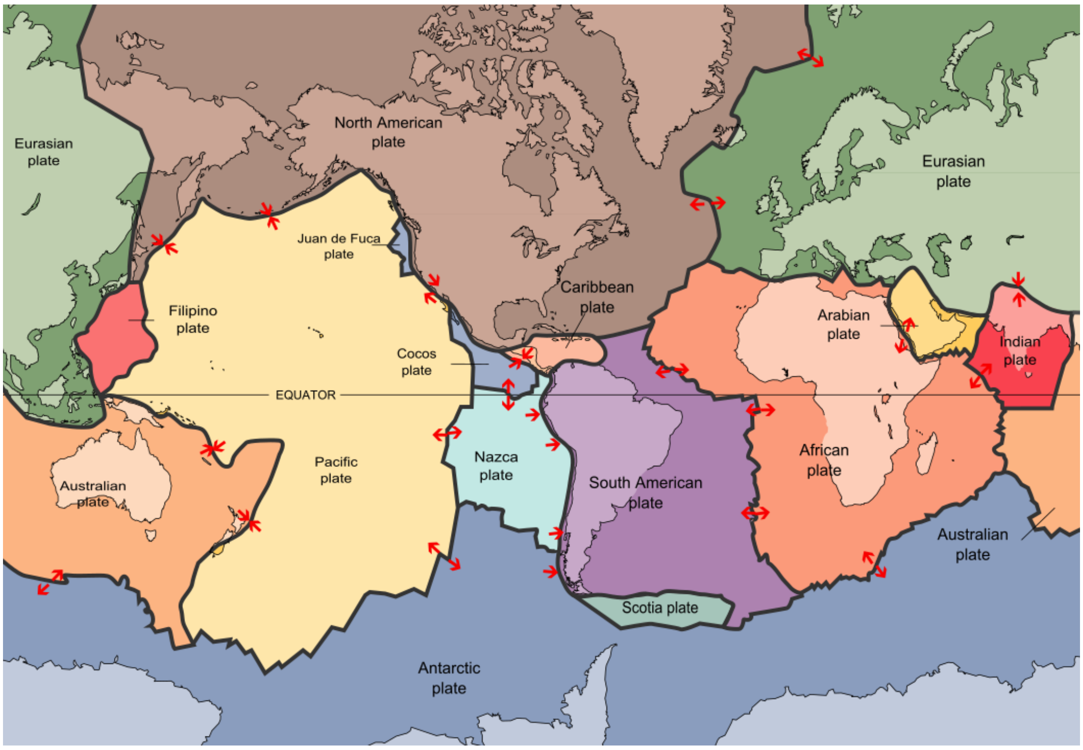

Figure 1: World tectonic maps (USGS)

2.3 Tectonic Settings of Region

Pakistan lies in important geotectonic position and has seismically active zones in north and south. The world is divided into fifteen tectonic plates. These plates are either converging or diverging from each other. These are reflected as shown in figure 1. Three main plates, namely Eurasian plate, Arabian plate and Indian plate are interacting around the region. These active plate boundaries are well defined and exposed in this region and maps developed by geological survey of Pakistan. Our region lies mainly on Indian tectonic plate as shown in figure 2.

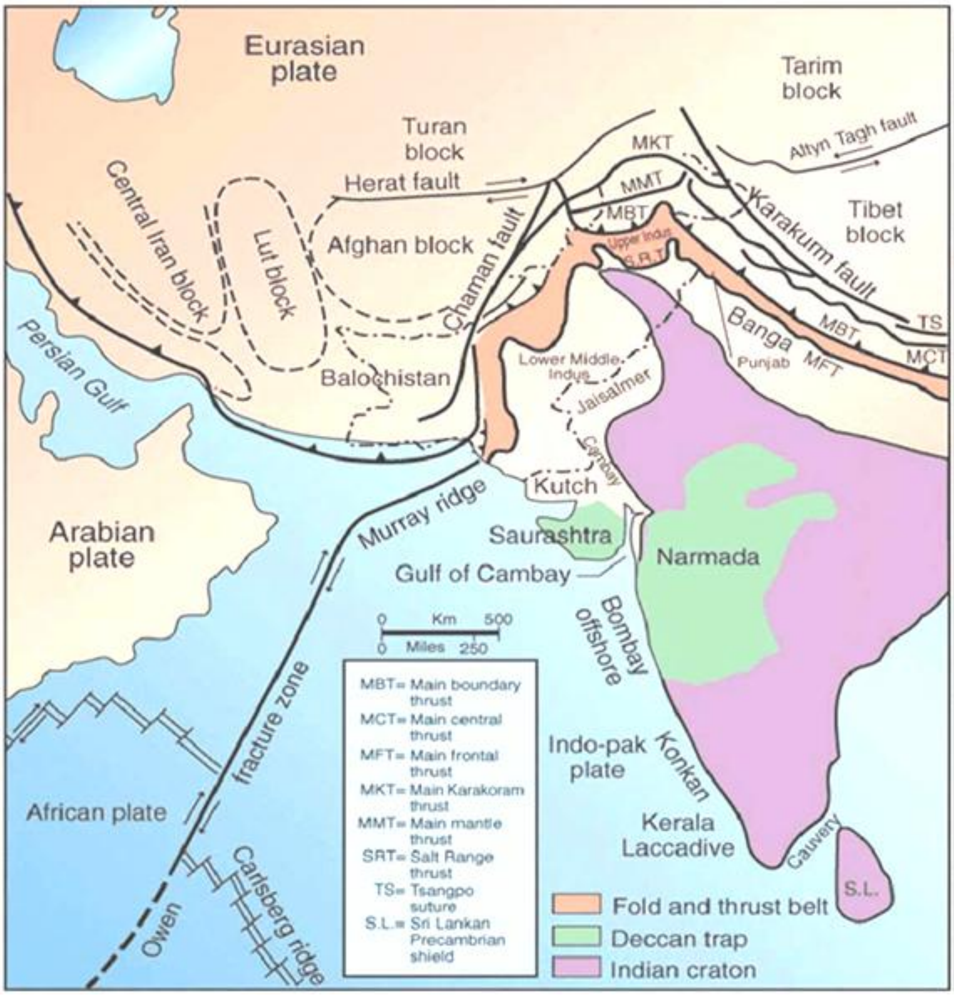

Figure 2: Indian and other interacting tectonic plates within Pakistan

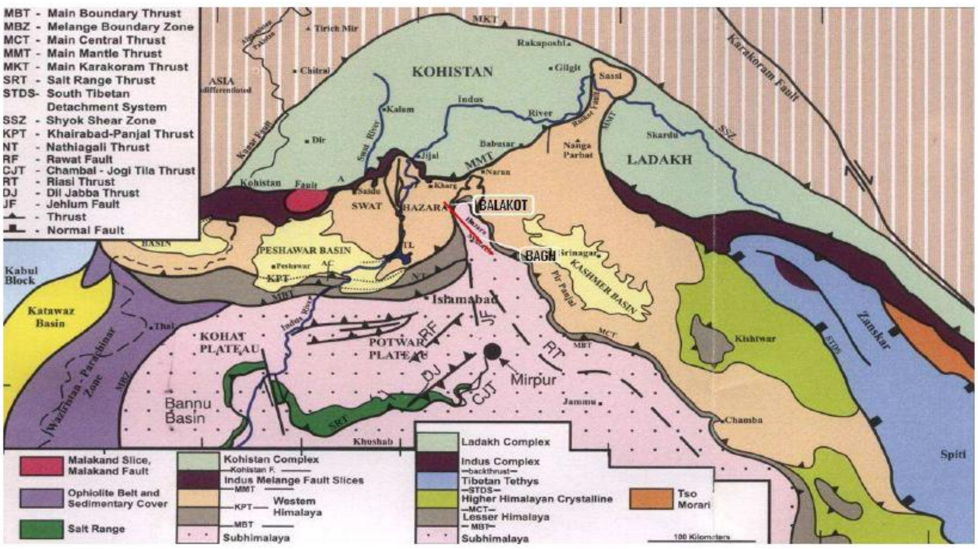

Figure 3: Fault distribution near Himalayan Thrust (Naveed et al, 2008)

The regional geological setting is marked by tectonic activity which continued upto relatively recent period. The Kundian - Mianwali depression is associated with one of the structural bends in the mountains of the extrapeninsula which is associated with the Baluchistan Arc and Himalayan Mountain System. Various such structural bends have been formed in western Himalayas, such as Hazara-Kashmir, Mianwali, Tank and Sibbi Syntaxial Bends, by the northward movement of the Indian Shield and the relative movement of Baluchistan Arc and Himalayan Mountain Ranges.

The Suleiman Range having a complex interface of strike slip and thrust movement along Chaman Fault Zone.

2.4 Seismotectonic Study around THAL DOAB

The Thal Doab area in Punjab plain is bordered by significant features/structures. The study region of Thal Doab is bordered on three sides by mountain ranges, the Salt Range in northeast, Surghar Range in north, Khisor and Marwat Ranges in west. The area south of these ranges is called the Punjab Plain and is the physiographic province in which Thal Doab is located. The Salt Range is distant from the lower Himalayas region by existing soan basin and Potwar Plateau as reflected in figure 5.

The northwest part of the Punjab Plain is a part of Mianwali Depression which is formed as a result of the distribution of the surrounding mountain ranges and represents an area where the Punjab Plain extends between the Salt Range and Khisor Range.

Each of the mountain ranges in the vicinity of the site forms escarpment slopes towards the site and gentle dip slope away from it. The Indus River which originates in the Himalayas drains the area through smaller tributaries. It comes out of the mountain ranges near Kalabagh and flows south with a braided pattern in Punjab Plain. The region area comprised of deep alluvial deposits of a maximum thickness of about 400 m, contains alternate clay-sand beds with minor conglomerate. This alluvium has been dumped by the adjoin river Indus and its tributaries.

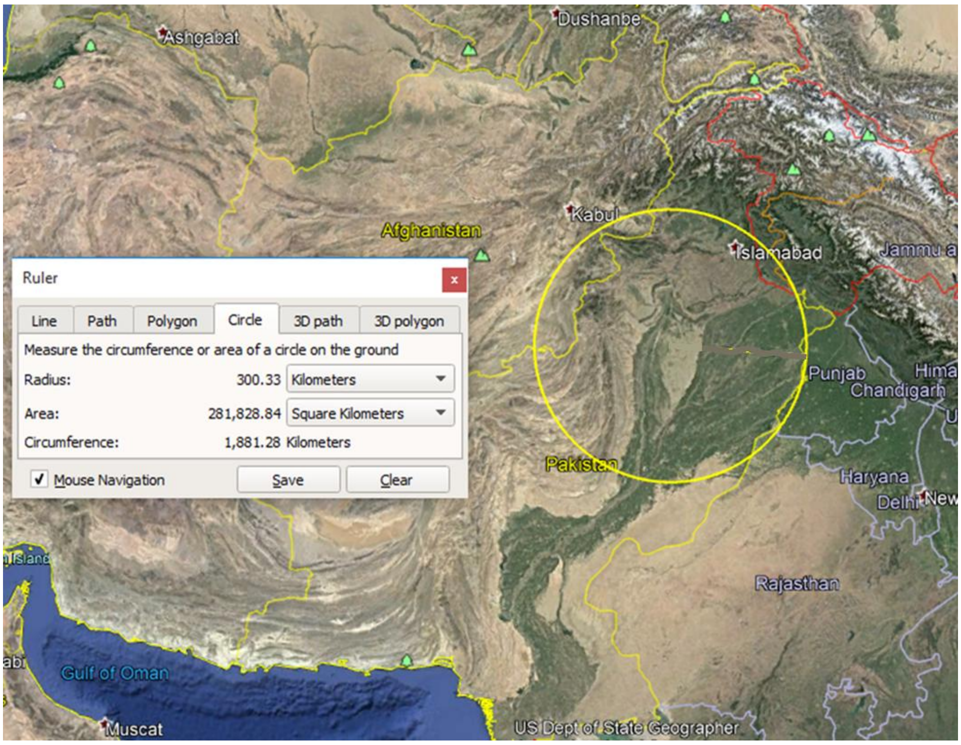

Figure 4: THAL DOAB, The Study Area

As per view of the previous knowledge, different filed studies, it became possible to redefine the main seismogenic zones/structures/provinces relevant to assess the potential seismic hazard at Thal Doab Area.

a) Hazara Thrust Zone

b) Salt Range and Potwar Province

c) Kalabagh Fault

d) Surghar Range Zone

e) Manglin Range Zone

f) Bhittani Range Structure

g) Sulaiman Range Zone

h) Khisor Range Structure

i) Marwat Range Structure

j) Bhakkar Fault Scarp Zone

k) Sargodha Ridge Zone

l) South Punjab Province

m) Mianwali - Khushab Province

n) Bannu Basin

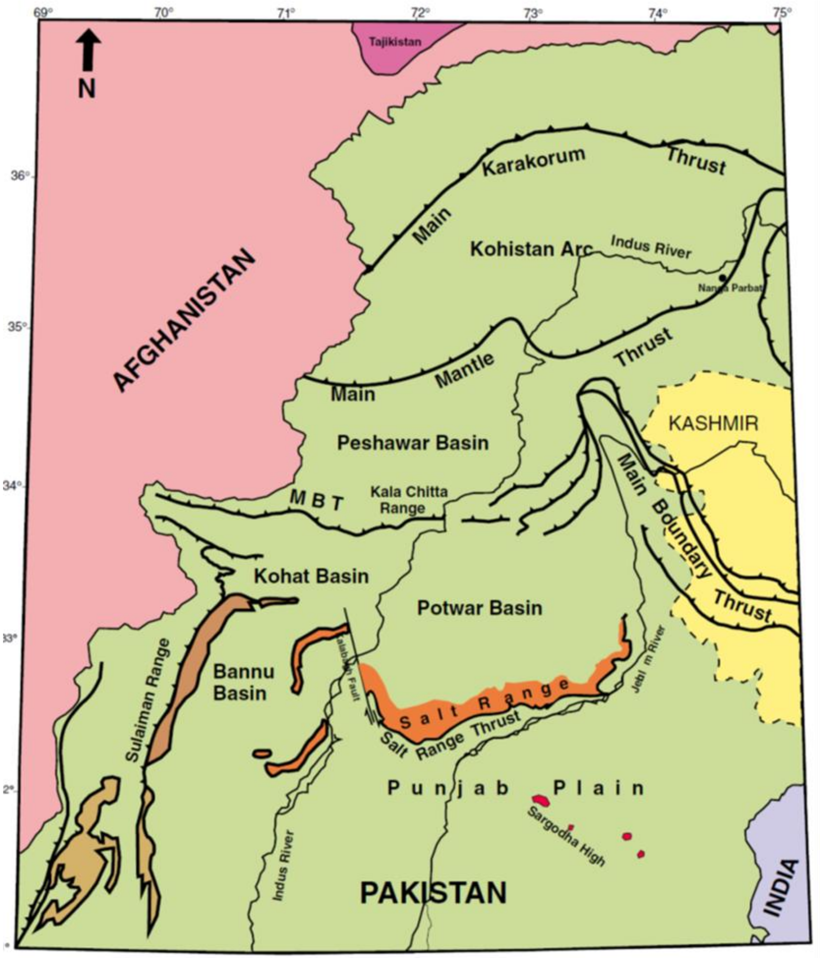

Figure 5: Potwar Basin and the Salt Range (modified after Gee 1983)

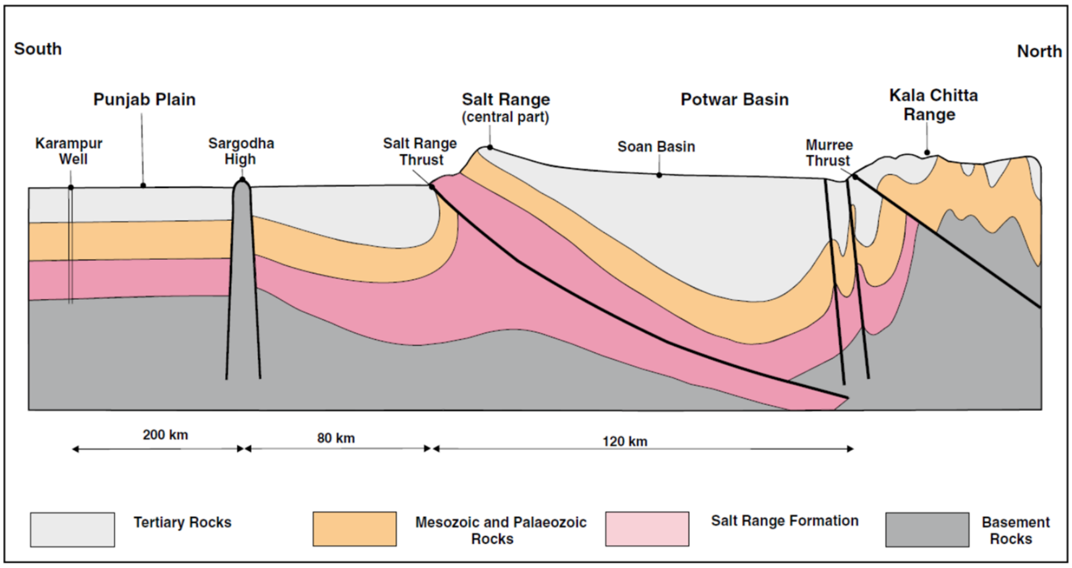

Figure 6: Cross section Potwar Basin and the Salt Range

The structures in the Hazara arc correspond to the Himalayan Main Boundary Thrust (MBT) which has been interpreted as a northward dipping thrust. The area has experienced historical seismicity of intensity VII to IX in the period from 25 AD to present. The postulated maximum Intensity is IX for this region which is equal to a magnitude of approximately 7.0.

The tectonic/fault structures found in salt range thrust zone are result of the response by the fold and thrust belt to the weak evaporite layer at the base, lining the decollement, and the changes in the underlying basement surface. The salt range evaporate system is of Eocambrian age and different studies shows that deformation is also taken place to some extent in its deeper layers. And it is also confirmed with the help of seismic study that basement is also faulted and it is also confirmed that the depth of basement in this area is about 9km and it decreases towards near south. Some spread outcrops are present Punjab plain area near to Sargodha such as Kirana. Salt.

This structural feature is present to the west of the site and is a part of Baluchistan Arc. A few strike slip and thrust faults have been mapped by Ali Hamza Kazmi 1979.

CHAPTER 3

3. RESEARCH METHODOLOGY

3.1 PSHA Methodology

The methodology of probabilistic seismic hazard analysis (PSHA) as defined by Cornell (1968) has four steps for assessment of seismic hazard:

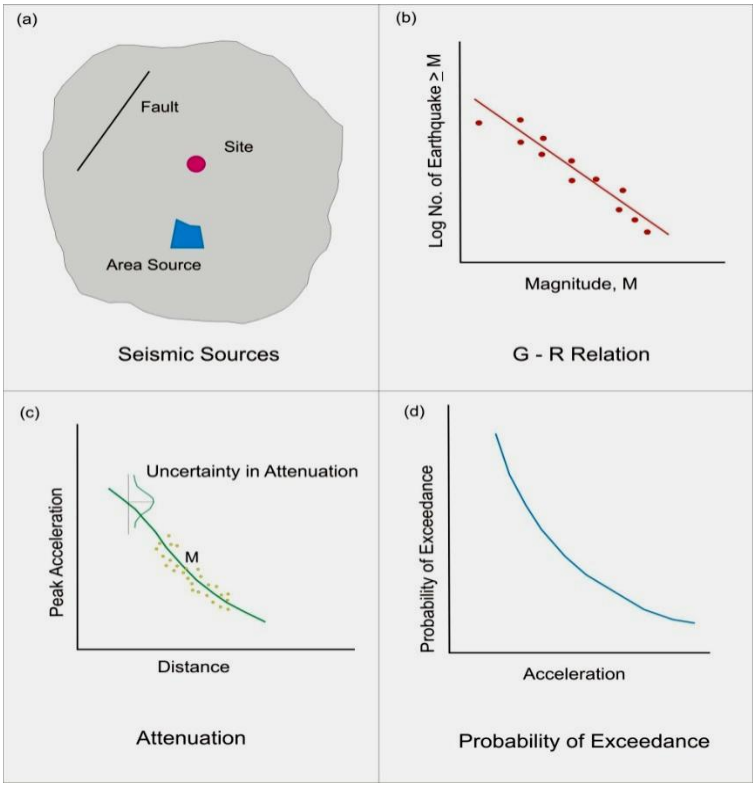

Figure 7: Scheme of performing PSHA

1) The first step starts with the identification and characterization of earthquake zones/sources. These sources may include the small faults within the region and also areal seismotectonic zones of uniform seismicity.

2) The second step is the calculation of seismicity recurrence parameters for zones identified in previous step, where each zone is described with recurrence relationship.

This relationship specifies the occurrence of an earthquake of a certain magnitude within the zone area in specified period of time.

Gutenberg-Richter relation is used for calculation of the recurrence rate of earthquakes as:

$$\log N(M) = a - bM \tag{2}$$

where, N(M) is annual number of earthquakes with a magnitude ≥ M, a is the logarithm of the number of events with magnitudes ≥ zero and b, is the slope of the distribution and controls the relative proportion of large to small earthquakes

3) The third step provides the estimation of the ground motion effects for an area by selection of earthquake attenuation relationships considering the distance and magnitude of an earthquake.

4) The fourth step provides the hazard curve by considering the effects of all the earthquakes within catalogue with locations in different zones and with their relevant probabilities of occurrence. The determination of uniform hazard curve provides the probability of exceeding different levels of ground motion level (such as peak acceleration) for the study area for any return period interval. The mathematical model is as under:

$$\boldsymbol{v(A > z) = N_{min} \cdot \iint_{mR} f_m(M) f_R(M,R) P(A > z|M,R) \times dM \times dR} \tag{3}$$

where ν is “annual rate of exceedance”.

- R, distance from region to site, M is the earthquake magnitude;
- N_{min} is the annual rate of earthquakes with magnitude ≥ minimum magnitude,
- $f_m(M)$ and $f_R(M, R)$ are the probability density functions, $P(A>z|M,R)$ is the probability of ground motion >z

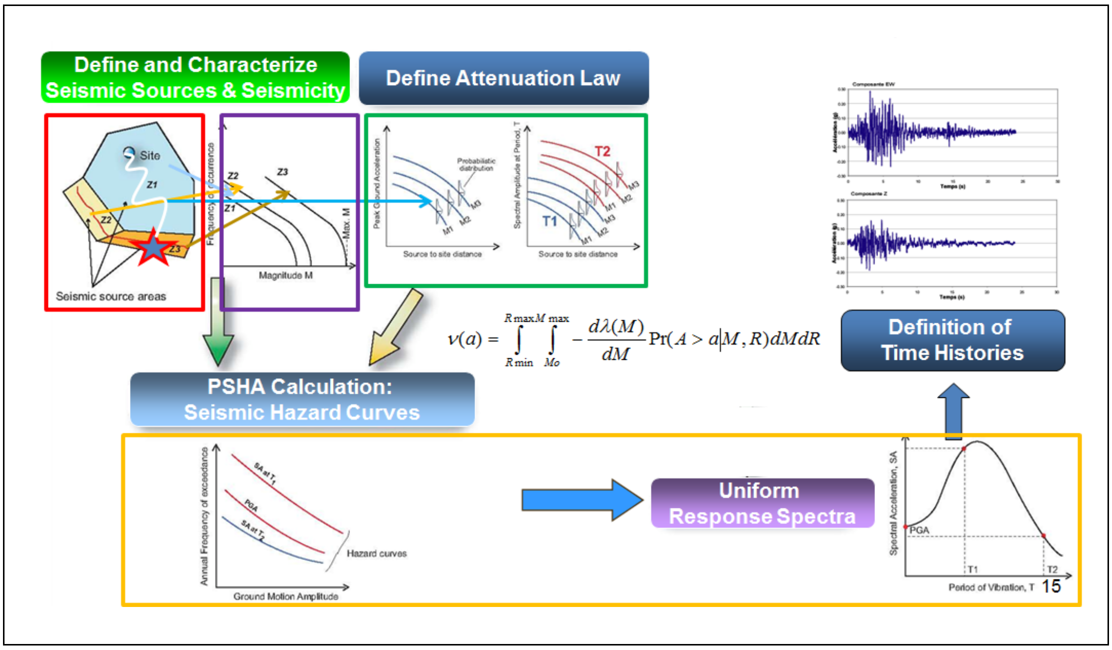

Figure 8 : PSHA Calculation Flow Process

3.2 Instrumental Earthquake Catalogue

Compilation of earthquake catalogue is preliminary step towards performing seismic hazard analysis. Formation of a composite earthquake catalogue is key for having best estimates for the seismic hazards. In current study a composite earthquake catalogue is compiled by using catalogue from United States Geological Survey (USGS), Pakistan Meteorological Department (PMD) and International Seismological Center (ISC). The time taken for the catalogue is from 1905 to September 2017. The catalogue is transformed into a uniform magnitude scale called moment magnitude (Mw). In order to compile the catalogue into uniformly Mw scale various updated empirical relationships have been used including Scodilis 2006, Akkar 2010 etc. However, Akkar 2010 is found most suitable relationship for calculation of Mw and used in further analyses as depicted in figure 8.

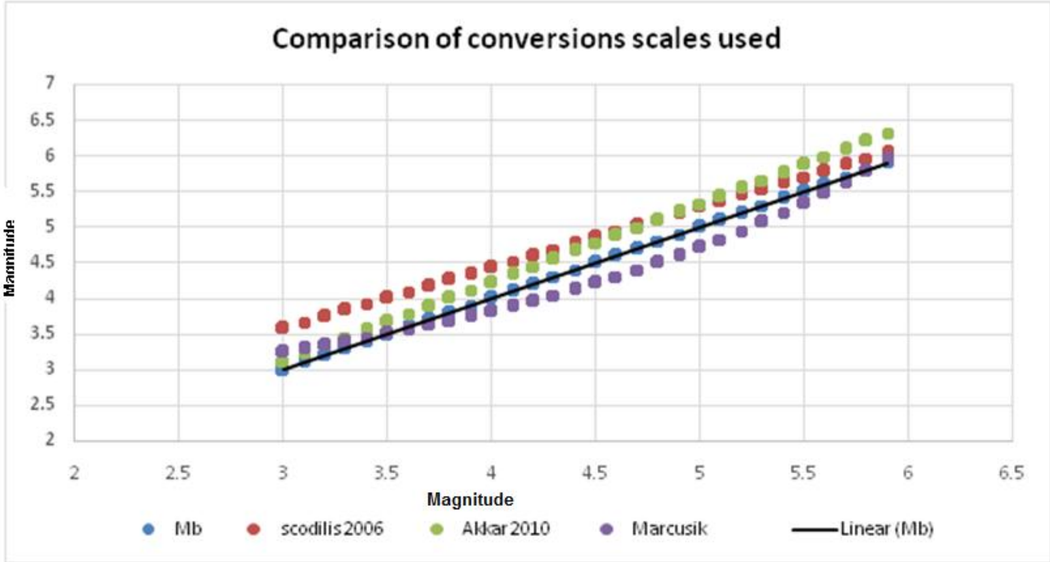

Figure 9: Comparison of Magnitude conversion relations

3.3 Seismicity Analysis

After compilation of earthquake catalogue into Mw scale, the catalogue is further processed to remove foreshocks and aftershocks from it and for this purpose an algorithm proposed by Reasenberg 1985 is used and this methodology is called catalogue declustering. Declustering is done by ZMAP software. By this methodology 666 clusters of earthquakes are found, i.e a total of 3184 events out of 25914. After declustering of the catalogue, it was further analyzed for period of completeness for different values of magnitudes as shown in figure 10 & 11. Similarly, histograms developed for depth, Mw and time to analyze the distribution of seismicity throughout the time from 1905 to 2017 as shown in figure 12. Catalogue was further assessed through a, b value plots from different methods like maximum likelihood and least square for evaluation of completeness interval and magnitude of completeness shown in figure 9.

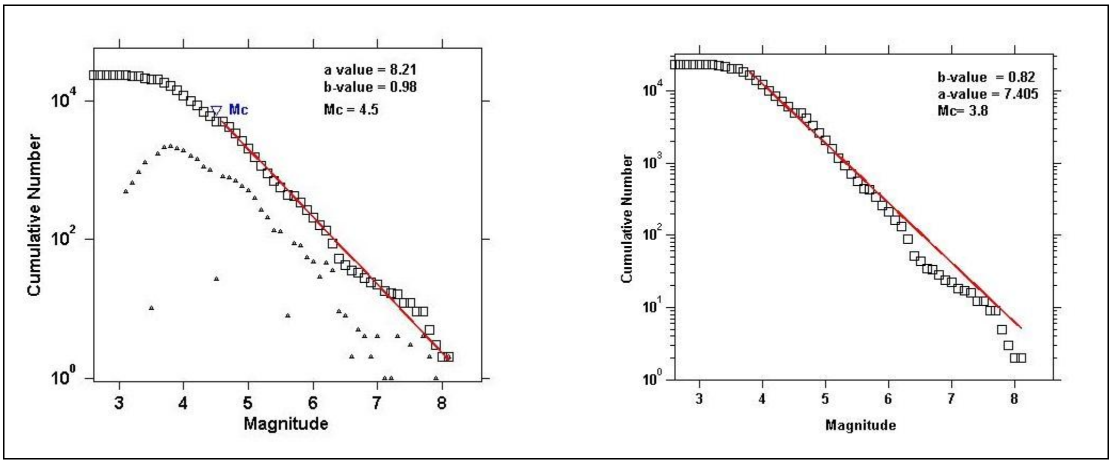

Figure 10: a, b values for catalogue using Max Likelihood & Least Square Method

The depth plot shows distribution of earthquakes with respect to depth. The histogram in figure 12 shows that most of events are in the range of shallow to moderate depth with some deep events.

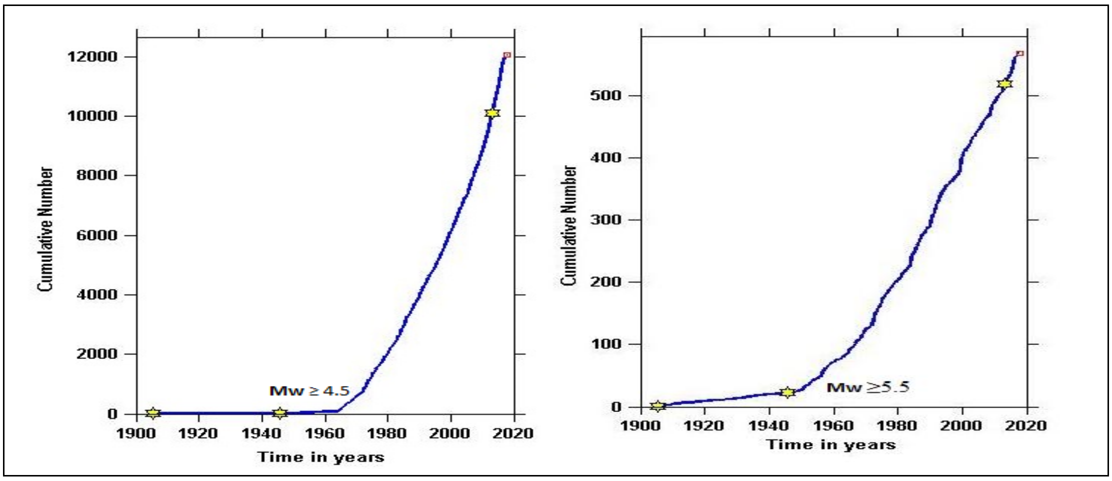

Figure 11: Magnitude Completeness for Mw4.5 & 5.5

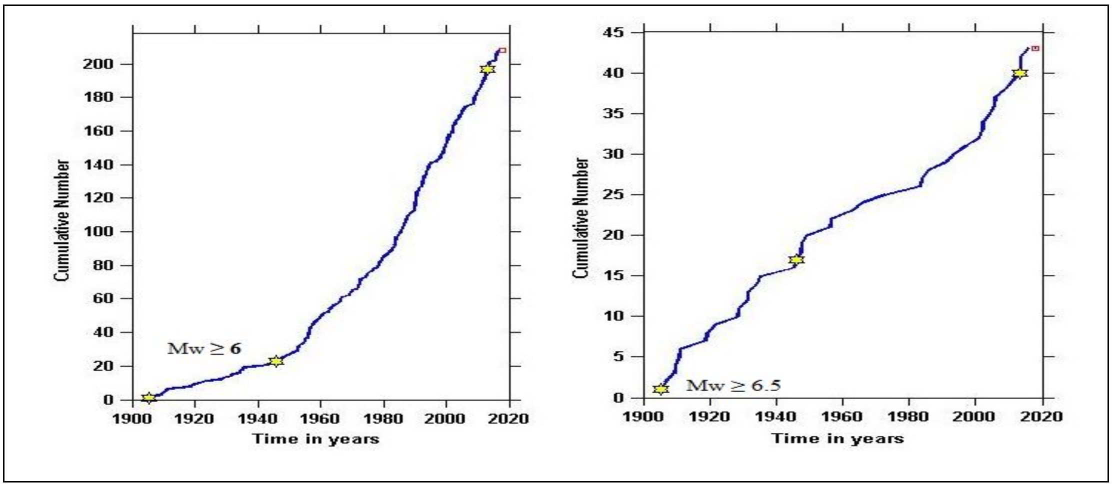

Figure 12: Magnitude Completeness for Mw6 & 6.5

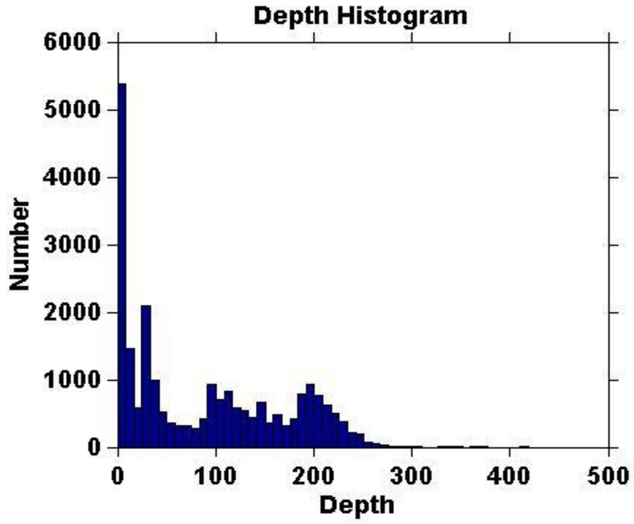

Figure 13: Earthquakes with respect to Depth

Once the catalogue is processed and analyzed, it is further converged into the area of interest in current study is Thal Doab region. Since the objective of the study is to establish ground motion parameters on the basis of probabilistic seismic hazard analysis (PSHA), so the seismicity and tectonics within an area of approximately 280,000Km^2 and 300Km in radius is considered. The 300km region is considered based on the engineering judgment and extension of seismotectonic structures. Therefore, frontal part of NW Himalayas, Sulaiman fold & thrust belt partially and areas of Punjab plain are considered.

3.4 Development of Area Source Model

A detailed PSHA can be performed through two ways one is based on areal source zone and other on fault source. In the current research, both approaches have been utilized to understand the seismic hazard in detail. However, in this report only area source model has been adopted due to un reliability of existing faults data for planner approach, but a study was performed based on data available in literature which showed that contribution in total hazard from faults are less than area sources. In this study, concept of large area source has been used representing current prevailing tectonic conditions, seismicity distribution and associated parameters like b values, focal depth distribution and style of faulting etc.

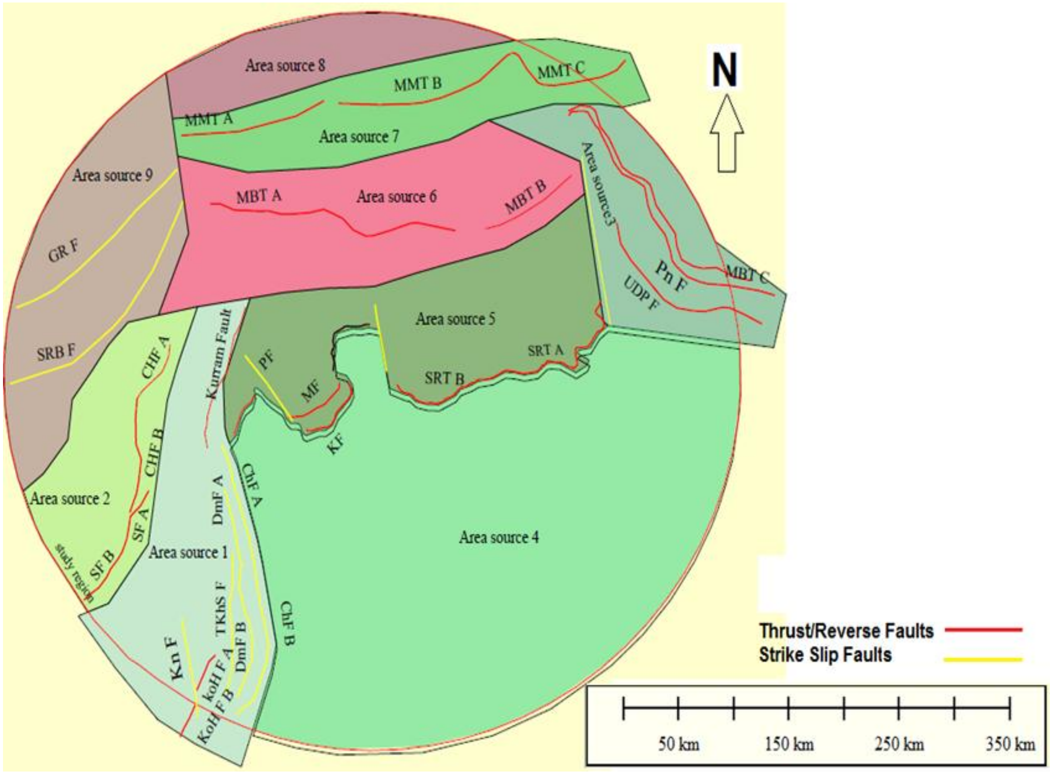

Figure 14: Area Source Model used for the studies

Demarcation of the area source boundaries is quite a tricky job which is performed carefully in light of local tectonic setting, seismicity pattern and expert opinion of geological engineering. A detailed schematic representation of selected area source zones and associated seismicity is given below in figure 14. Total nine area sources have been selected on the basis of seismicity, tectonic setting and faults present with the region. Seismicity in each area has been extracted through ZMAP software and a, b values have been found accordingly through three different approaches which includes method of likelihood, least square and Weichert 1980.

3.5 Determination of Maximum Magnitude for Areal Sources

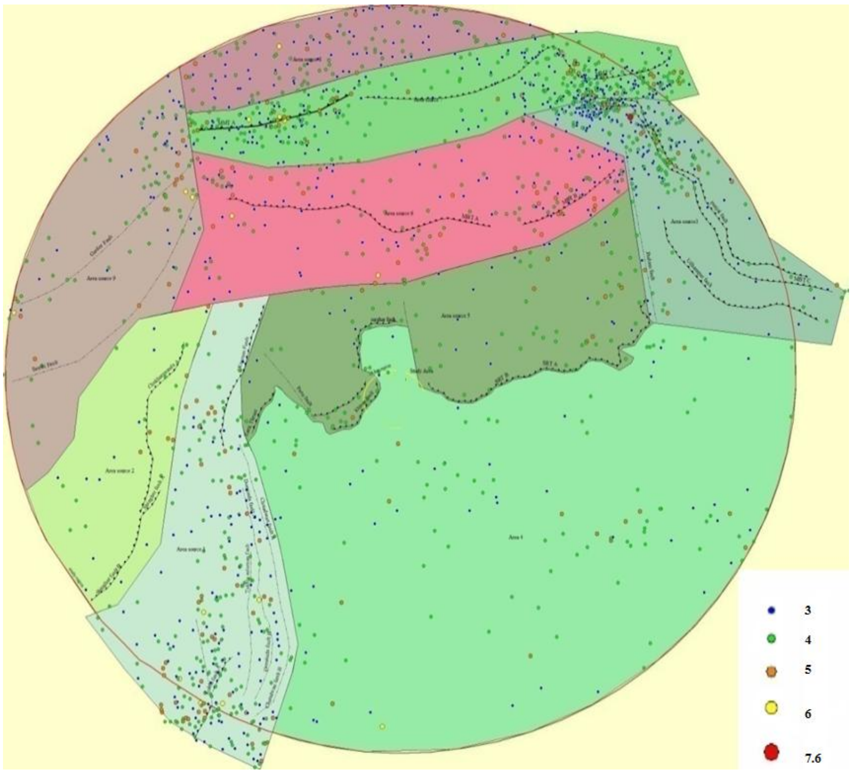

Figure 15: Seismicity for Region of 280,000Km^2 from 1905 to 2017

Calculation of maximum magnitude for source zone is one of the key steps in PSHA. The maximum magnitude is the largest expected magnitude with in an area or planner source. The determination of M_{max} is tricky job due to associated uncertainties, especially in terms of earthquake rupture process etc which are required to be addressed in detail. Over the years methods to estimates M_{max} have been evolved due to availability of new data and methodologies, especially for zones without any known geological structure. In current study, M_{max} has been calculated based on latest data set and methodologies available which includes compilation of earthquake catalogue, usage of maximum observed magnitude in each region and planner source, geological and imagery evidences and statistical approaches. After compilation of all data set three different approaches have been used to calculate M_{max} which include,

M_{max} based rupture area relationship by Wells & Copper Smith and other etc. The M_{max} assigned to each source zone based on faults presents are given in table 1 with assigned weights. Since site/study area lies in a zone without any known geological structure therefore Bayesian approach originally proposed by EPRI (1994) has been used to assign M_{max}.

Table 1: Magnitudes and weights assigned to area sources

	Weight 0.25	**Weight 0.50**	**Weight 0.25**
Source Zone	Mmax 1	Mmax 2	Mmax 3
1	7.48	7.58	7.68
2	7.63	7.84	8.05
3	8.14	8.46	8.78
4	6.5	6.75	7.00
5	7.26	7.3	7.34
6	7.78	8.06	8.34
7	8.16	8.39	8.62
8	7.67	7.84	8.01
9	7.88	8.05	8.23

Table 2: Activity rates determined through Max Likelihood(MLE), Least Square (LSE) and Weichert (1981)

	Activity Rate		
	ZMAP MLE	ZMAP LSE	Weichert (1981)
Source Zone	Weight 0.33	Weight 0.33	Weight 0.34
1	1.6140	1.2969	1.8800
2	0.1224	0.1342	0.1690
3	1.3737	0.8089	1.0000
4	0.4874	0.4763	0.6200
5	0.4602	0.4344	0.6200
6	0.5727	0.6651	0.8300
7	1.2103	1.2385	1.6600
8	0.3740	0.3740	0.4900
9	0.5223	0.5532	0.7100

Each parameter of the source model was included in the logic tree with its center and the range; in other words; epistemic and aleatory uncertainties for activity rate, b-value, maximum magnitude, dip angle and source depth were considered.

3.6 Ground Motion Prediction Relationships

The ground motion parameters and response spectrum for a region mainly depends on earthquake magnitude, its distance with presence of type of medium and the local soil conditions. Ground motion parameters are usually established by using the region specific empirical attenuation relations developed from actual record or for similar regions of the world. As region specific empirical relation are not available. Therefore, attenuation relations developed for different regions of the world are studied and most suitable ones, rich in database such as developed by PEER are used. Selection to employ suitable attenuation model is the crucial step in hazard calculations after determination of relevant parameters associated with areal source. The attenuation models developed for a region depends on vast and rich dataset. This dataset may be variable as compare to other regions of the world. Pakistan lies in tectonically dynamic region but the available dataset and instrumental record is scarce.

The development and use of region specific attenuation models is recommended, however due to some constraints; attenuation models developed for similar site region conditions can be adopted. In view of above discussion, attenuation models developed by PEER under NGA-WEST 2 project are used for this study in line with conditions suggested as under:

- A distance of about upto 300 km radius for region of earthquake happening
- Moment magnitude (Mw) should be of 3 to 8.5
- Shear wave velocity range of about 150 m/sec to1500 m/sec

Based on above, following suitable attenuation relationships are used:

1. Abrahamson and Silva NGA-WEST 2 Model
2. Campbell and Bozorgnia NGA-WEST 2 Model
3. Chiou and Young NGA-WEST 2 Model
4. Boore and Atkinson NGA-WEST 2 Model

5. BCHydro (2010) Subduction

3.7 Development of Logic Tree

The development of logic tree facilitates by propagating the uncertainties included in the analysis. It is tried to include all possible scenarios including dips, b values, activity rates, calculation of maximum potential magnitude and usage of attenuation models etc as shown in figure 15.

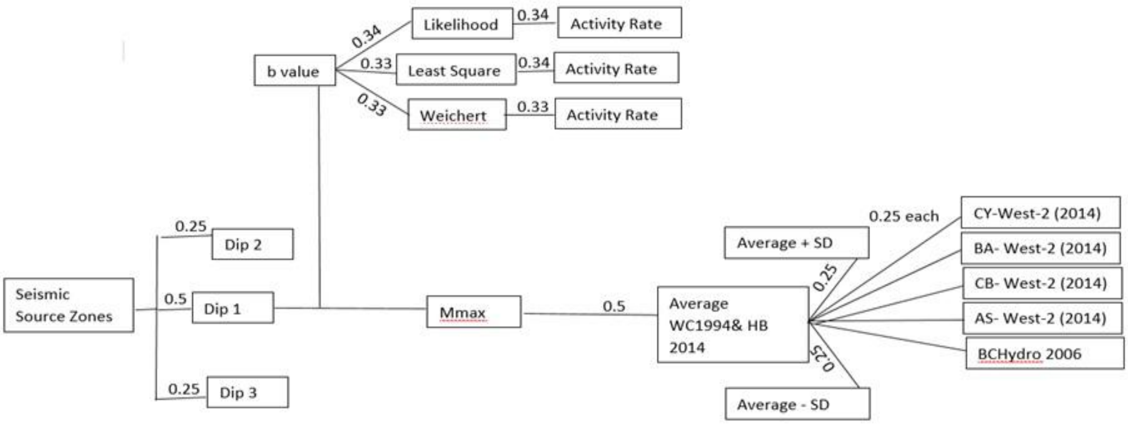

Figure 16: Detailed logic tree and uncertainties propagation

3.8 Geotechnical Site Parameters

Shear wave velocity is one of the important geotechnical site parameter used in PSHA which is obtained through borehole surveys. In case of this site, shear wave velocity measured in top 30 meters is about 360 m/sec. However, bottom boundary of soil layers is established at 150 meters with shear velocity of about 550 m/sec.

For the PSHA analysis, the V_{S30} = 550 m/s is selected as the representative value of the soil conditions based on the interpretations of the seismic site survey results. Since the study area site is a deep soil site where geological bedrock is not encountered in borehole up to 171 meters. This is the reason PSHA analysis was not conducted for the surface V_{S30} value because the surface soils have been removed during the construction of the foundation. Instead, the engineering bedrock is defined as the stiffest soil that was reached in geotechnical boreholes at 150 m and the analysis were conducted at the bedrock level. If the boreholes were deeper, stiffer soils might have been reached. However, extending the boreholes deeper to capture the NEHRP B/C boundary (V_{S30}=760 m/s) is recommended in future.

3.9 Representative Soil Profiles

Based on the field geotechnical data available for THAL DOAB area, representative shear wave velocity profiles to be used in the 1-D site response analysis are developed. Groundwater was not modeled in the site response module. Representative soil profiles consist of seven (7) soil layers. The top soil layer at the surface with relatively small shear wave velocity values (Vs=225-275 m/s) represents the top soil. The top soil layer was followed by 20 m thick layer has a shear wave velocity range of 275 - 350 m/s. The bottom layer (engineering bedrock) is established at 150 meters with shear wave velocity of around 520-540 m/sec and UHS is also generated at this depth. The soil profile prepared is shown in figure 16.

The current analysis includes the effect of soft surface soils on the design ground motions by conducting a site-specific equivalent linear 1-D site response analysis. The inputs of the modulus degradation and damping curves are important for 1-D site response analysis that represents the soil layers properly.

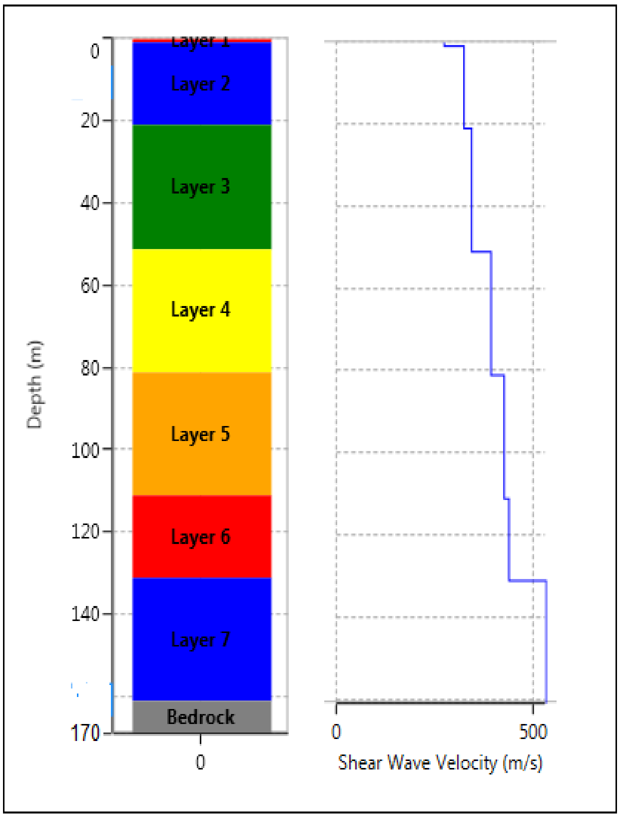

Figure 17: Soil profile prepared for the study

These curves are used to equalize the determined non-linear hysteretic stress-strain performance of the soil in equivalent linear analyses. The modulus reduction aspect is affected by the mean effective confining pressure of sandy soils. The curve proposed by Seed and Idriss(1991) is utilized. Its lower limit is used for the top soil layers and upper limit for other layers. The curves for sandy soil are given in figure 17.

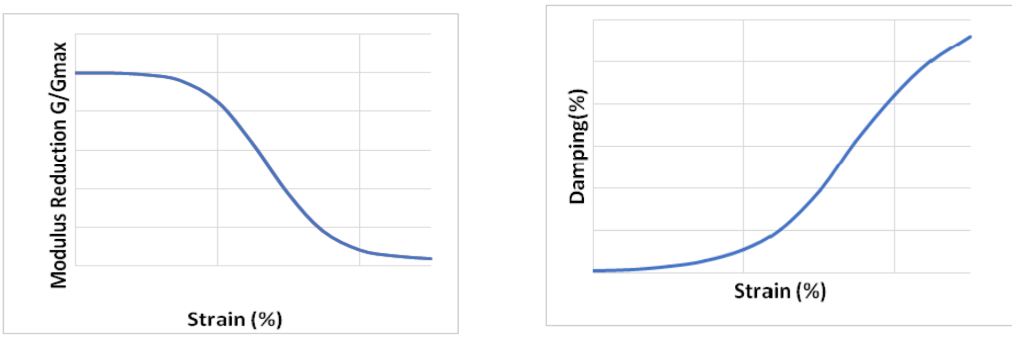

Figure 18: Modulus degradation and damping curves for sandy soil

Other geotechnical parameters (such as density of the soil layers, etc.) are selected carefully based on the laboratory tests and documented values reported in literature.

3.10 Site Response Analysis

The site response analysis for THAL DOAB area is conducted using the software package DEEPSOIL V 7.1. This is 1-D site response analysis program with graphical user interface (Hashash et al., 2012). The equivalent linear capability of the DEEPSOIL was initially based on SHAKE methodology developed by Idriss and Seed (1968). The soil layers were modeled as sand layers with taking reference unit weight, damping ratio and modulus reduction curves were adopted from Seed at al. (1985/1991). It is notable that the soil layers in this study are simplified layers and more detailed analysis can be conducted if further information about the geotechnical laboratory test results is available.

3.11 Time Histories

Selection of time histories is important for the dynamic analysis of structures against earthquake effects. According to California Building Code (CBC-2003) and ASCE/SEI 43-05, pairs of available horizontal ground motion time history components (longitude & transverse) are selected. Based on the considerations given above, seven horizontal ground motions are selected as shown in figure 18. These time histories are the compatible time histories to actual site conditions of site used in PSHA which includes dominating magnitude range, distance range and shear wave velocities etc.

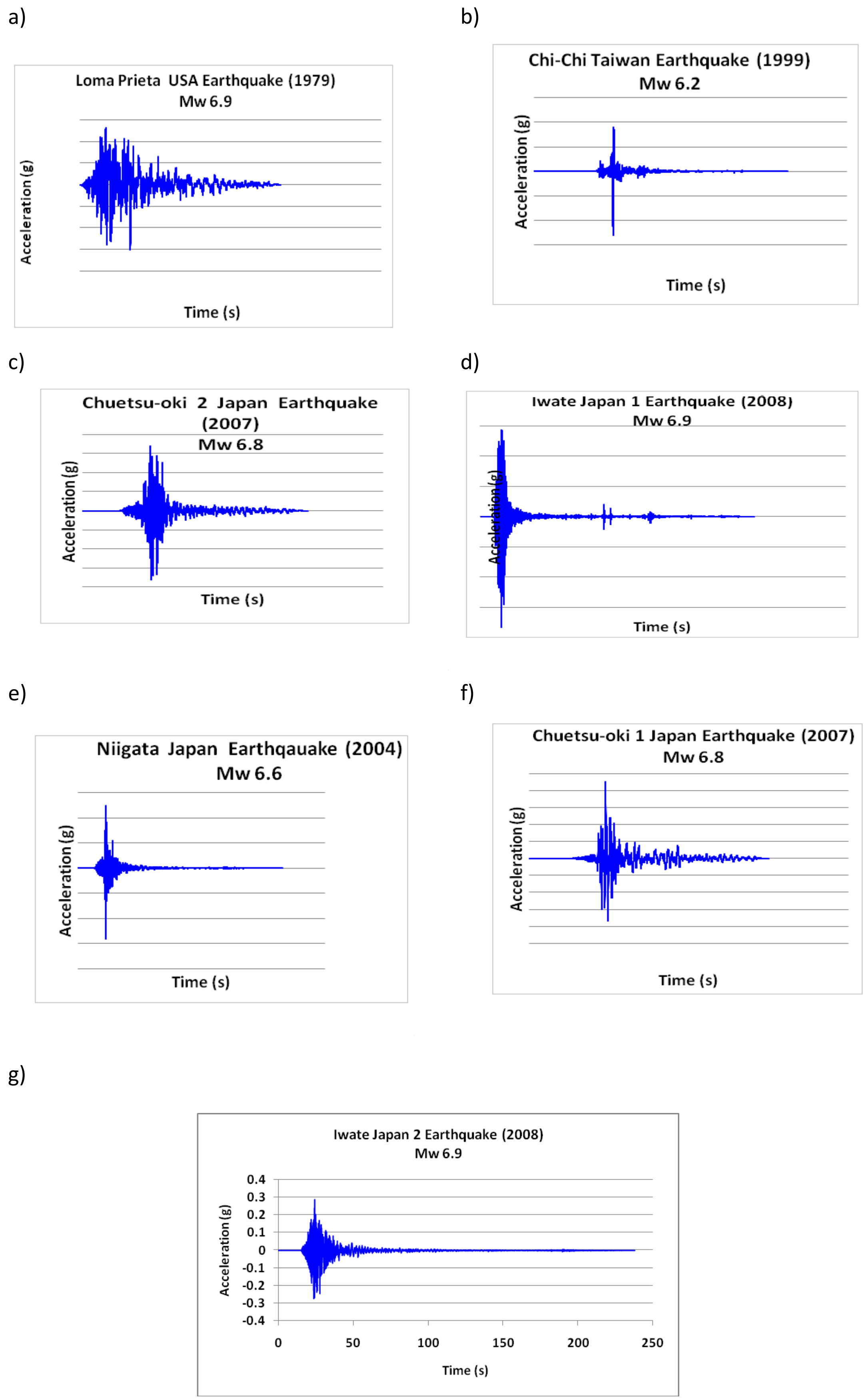

Figure 19: Original Time Histories used for 1D Site Specific Response Analysis

3.12 Damping Scaling Factors

The calculation of spectrum attenuation coefficients for different damping ratios is required for design input. In order to determine the DSFs, an empirical approach proposed by Rezaeian et al. (2014) has been employed and given in figure 15 and table 3 .

$$\ln(DSF) = b_0 + b_1 \ln(\beta) + b_2 (\ln(\beta))^2 + (b_3 + b_4 \ln(\beta) + b_5 (\ln(\beta))^2) M + (b_6 + b_7 \ln(\beta) + b_8 (\ln(\beta))^2) \ln(R_{rup} + 1) \quad (4)$$

Which include the magnitude, rupture distance and β as shown in Equation 3, where β is the damping ratio in percentage (e.g., β =2 for 2% damping); M is the magnitude; Rrup is in km; b0 to b8 are the period-dependent regression coefficients. The UHSs developed for bedrock and surface at 475 and 10,000years for different damping values are given in figures 16-19. The selected GMPEs are developed considering inherently 5% reference damping ratio and same damping ratio is also used in this study.

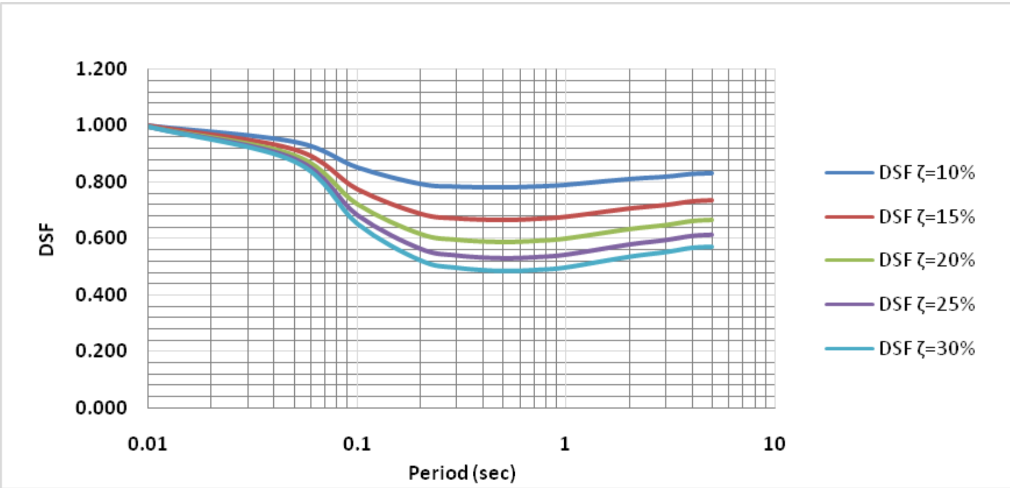

Figure 20: DSFs based on Rezaeian et al. (2014)

Table 3: DSF based on Rezaeian et al. (2014) method

Period	DSF ζ=10%	DSF ζ=15%	DSF ζ=20%	DSF ζ=25%	DSF ζ=30%
0.01	0.999	0.998	0.997	0.996	0.995
0.05	0.942	0.913	0.895	0.883	0.873
0.1	0.853	0.774	0.722	0.683	0.653
0.2	0.795	0.687	0.616	0.565	0.525
0.3	0.785	0.671	0.595	0.541	0.498
0.5	0.783	0.665	0.587	0.531	0.487
0.75	0.787	0.670	0.592	0.536	0.492
1	0.792	0.677	0.600	0.543	0.500
2	0.812	0.705	0.633	0.579	0.537
3	0.820	0.718	0.647	0.595	0.553
4	0.830	0.731	0.662	0.610	0.568
5	0.832	0.734	0.666	0.614	0.572

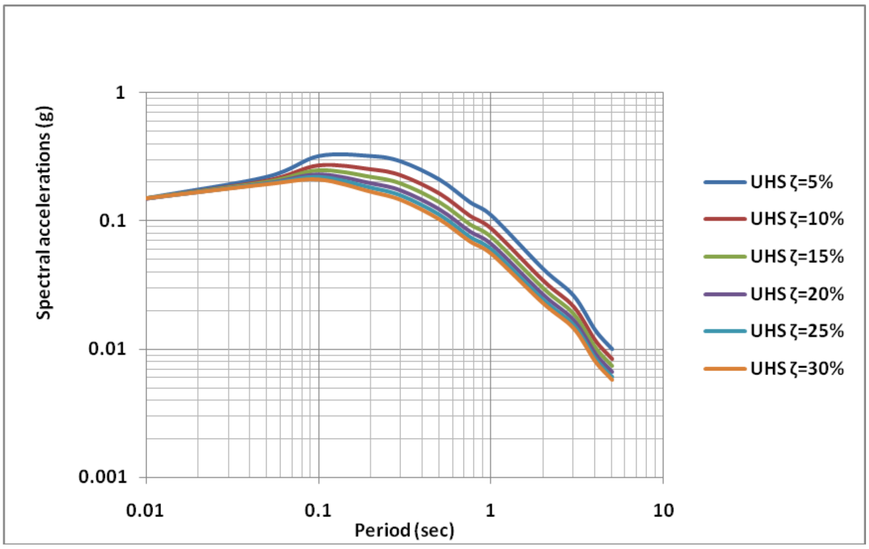

Figure 21: 475 years UHS (bed rock) for different damping ratios

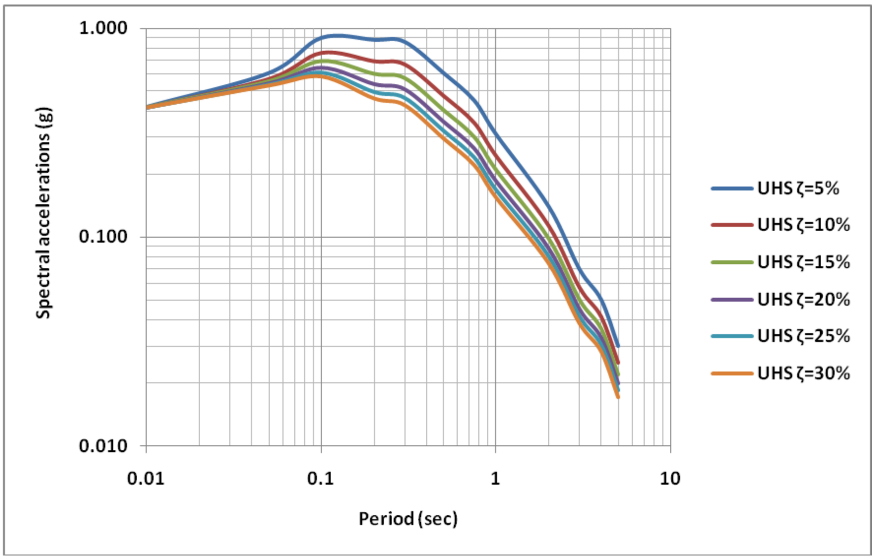

Figure 22: 10,000 years UHS (bed rock) for different damping ratios

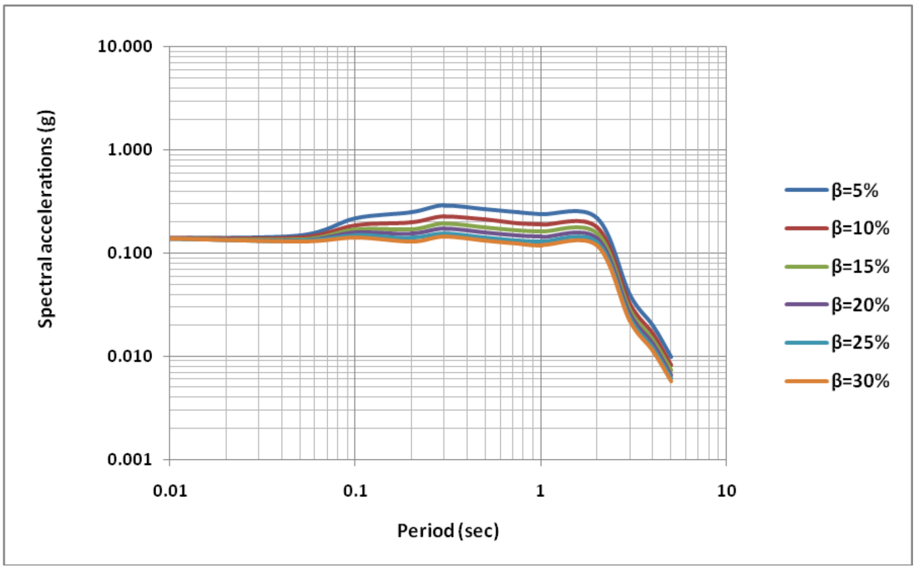

Figure 23: The 475 years spectra (surface) for different damping ratios

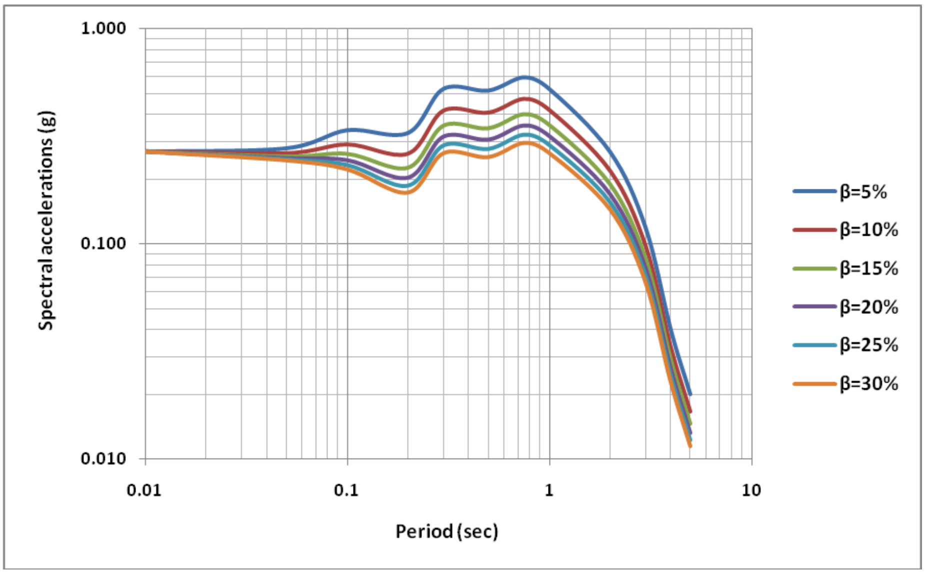

Figure 24: The 10,000 years spectra (surface) for different damping ratios

CHAPTER 4

4. RESULTS & DISCUSSION

4.1 Hazard Curves & Uniform Hazard Spectrum

The hazard curves determined after PSHA analysis for peak ground acceleration (PGA) for various annual rate of exceedance for 5% damping for Thal Doab region are shown in Figure 16. The annual hazard levels corresponding to 475 years (10% chance of exceedance in 50 years) and 10,000 years (1% chance of exceedance in 100 years) return periods are specified. Analysis results showed that the site-specific PGA value for 475 and 10,000 years return period is 0.15g and 0.42g respectively as shown in Figure 16. The contribution by each source zone to the total hazard for PGA is shown in Figure 16. According to Figure 10, the "zone 4 and 5" shows the maximum contribution towards the total hazard for Thal Doab Area.

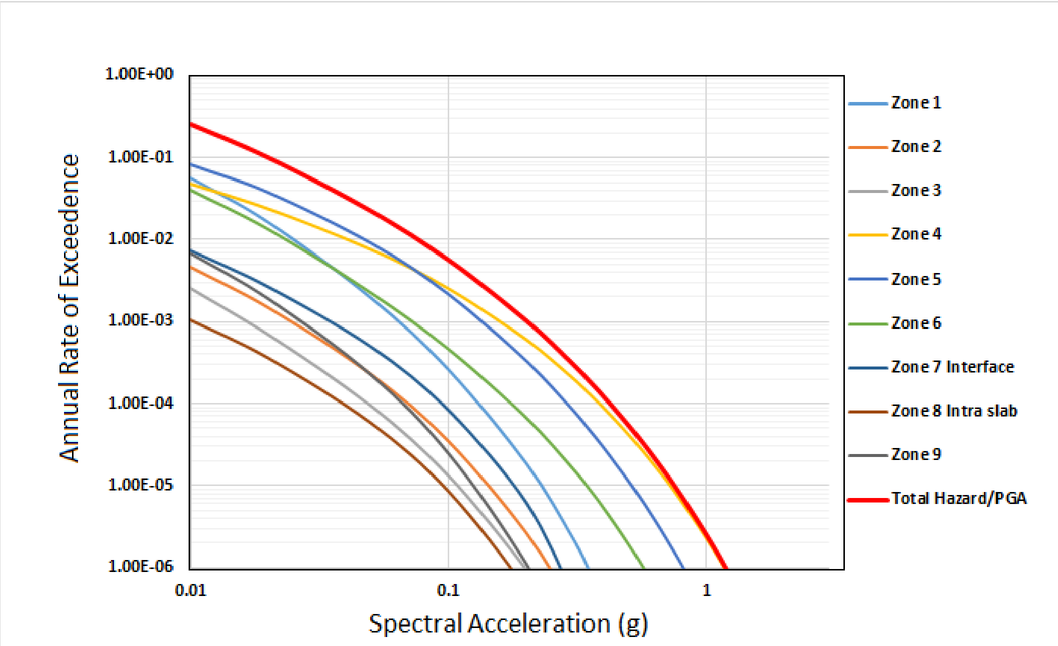

Figure 25: Total hazard and contribution of each area source hazard

The approach of Uniform Hazard Spectrum (UHS) is applied for development of design spectra based on this analysis. The UHS is a result of the computation for seismic hazard at different time periods. The ground motion is computed at these spectral time periods for a specified probability level. The UHS exclude the spectrum for a single earthquake as the hazard is computed independently for each spectral period. The UHS for THAL DOAB area corresponding to return periods of 475 years and 10,000 years is shown in Figure17.

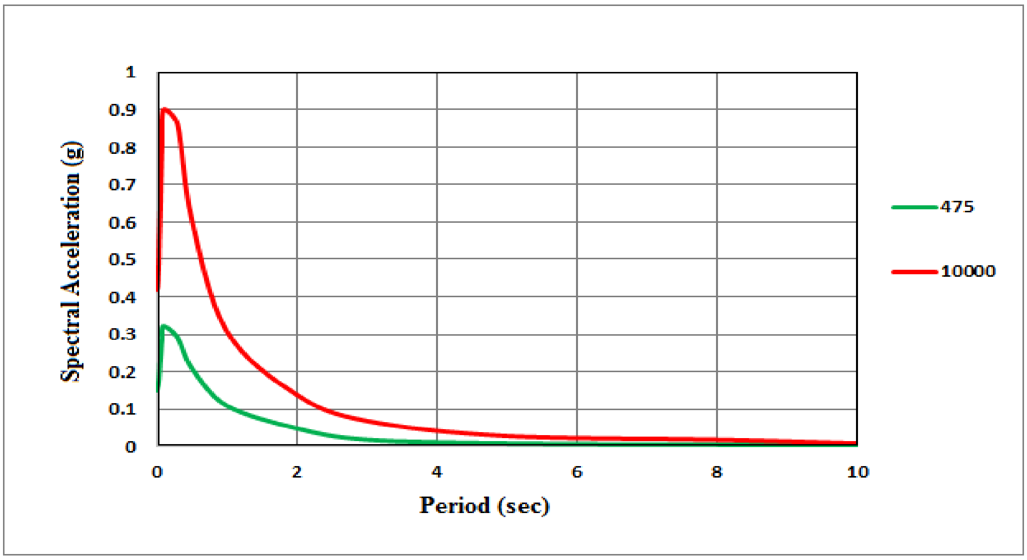

Figure 26: Uniform Hazard Spectra (UHS) for 475 and 10,000 years (at 150 m depth)

4.2 Deaggregation

The deaggregation plots for PGA for 475 & 10,000 years return periods are shown in Figure 18 &19, respectively. Figures 18, indicates that the hazard is dominated by a nearby scenario (M=5.5-6.0, 10-20 km) for shorter spectral periods both for 475 years and similarly, for 10,000 years' hazard is dominated by a scenario (M=5.5-6.0, 20-30 km) as shown in figure 19.

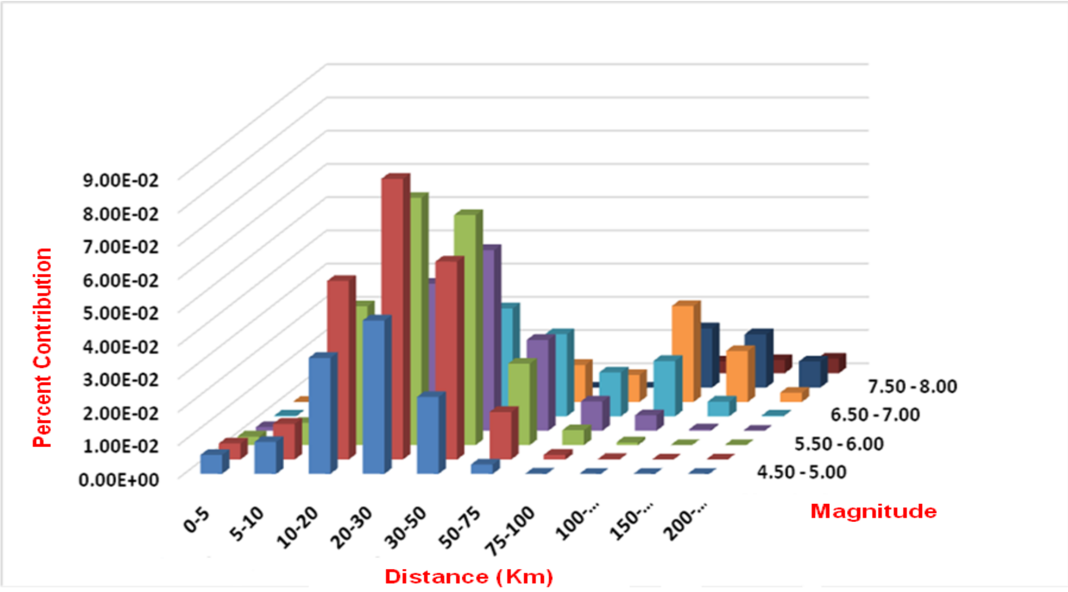

Figure 27: Deaggregation plot for 475 years

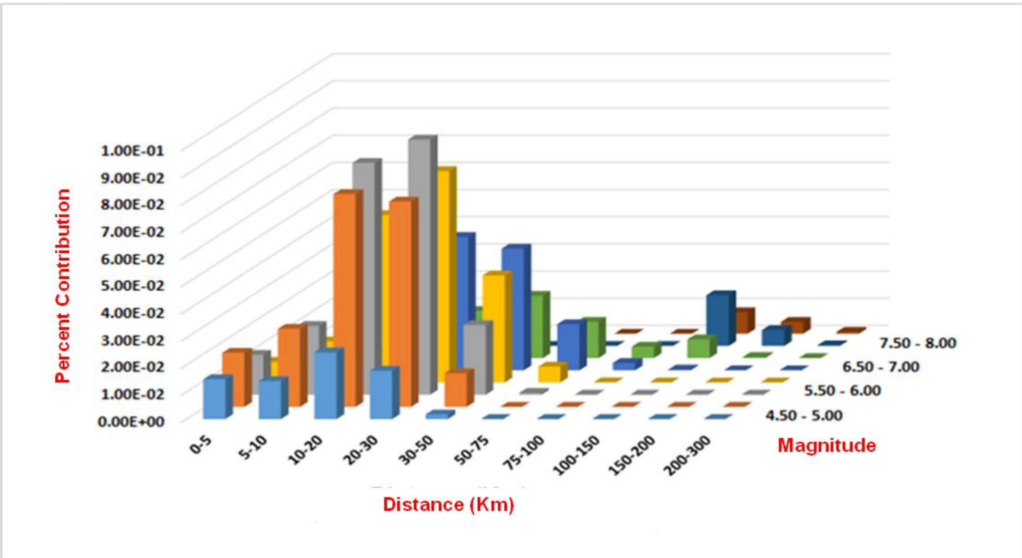

Figure 28: Deaggregation Plot for 10,000 years

4.3 Design Ground Motions

For the PSHA analysis, the V_{S30} = 550 m/s was selected as the representative value of the reference soil conditions based on the interpretations of the seismic site survey conducted for region. Seismic hazard analysis resulted in ground motion parameter of PGA value at the bedrock for 475 and 10,000 years return period as 0.15g and 0.42g respectively. The design spectra based on the PSHA outputs were developed by using the Uniform Hazard Spectrum (UHS) method. The UHS at the bedrock and the design spectra at the surface for Thal Doab area corresponding to 475 years and 10,000 years return periods are shown in Figure 29 &30.

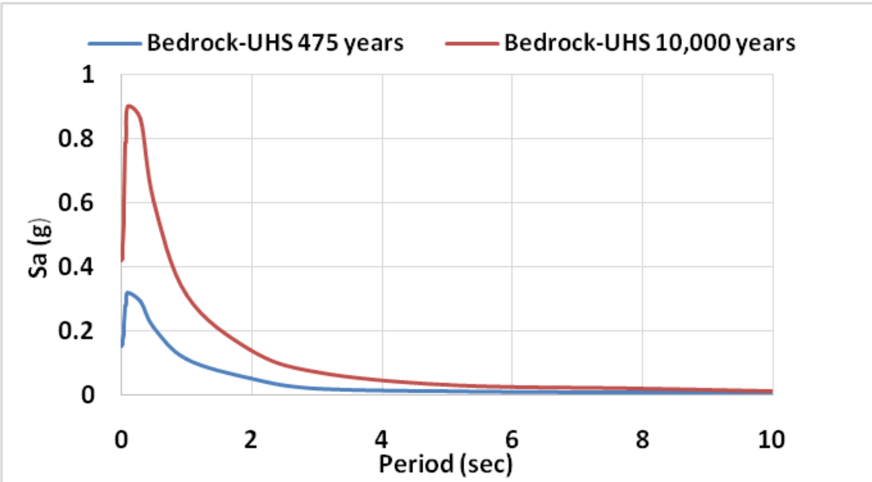

Figure 29: UHS at bedrock for 475 and 10,000 years

4.4 Site Specific Ground Response Analysis Results

The average site-specific & bedrock response spectra for 475 and 10,000 years return periods are provided in Figure 29 & 30 for Study Area Site respectively. The spectra showed that the ground motions are observed for site for 475 and 10,000 years after site response resulted de amplification and high deformation of soil as shown in figure 26 & 27 with horizontal displacement of about 0.18 m as shown in figure 28.

a) b)

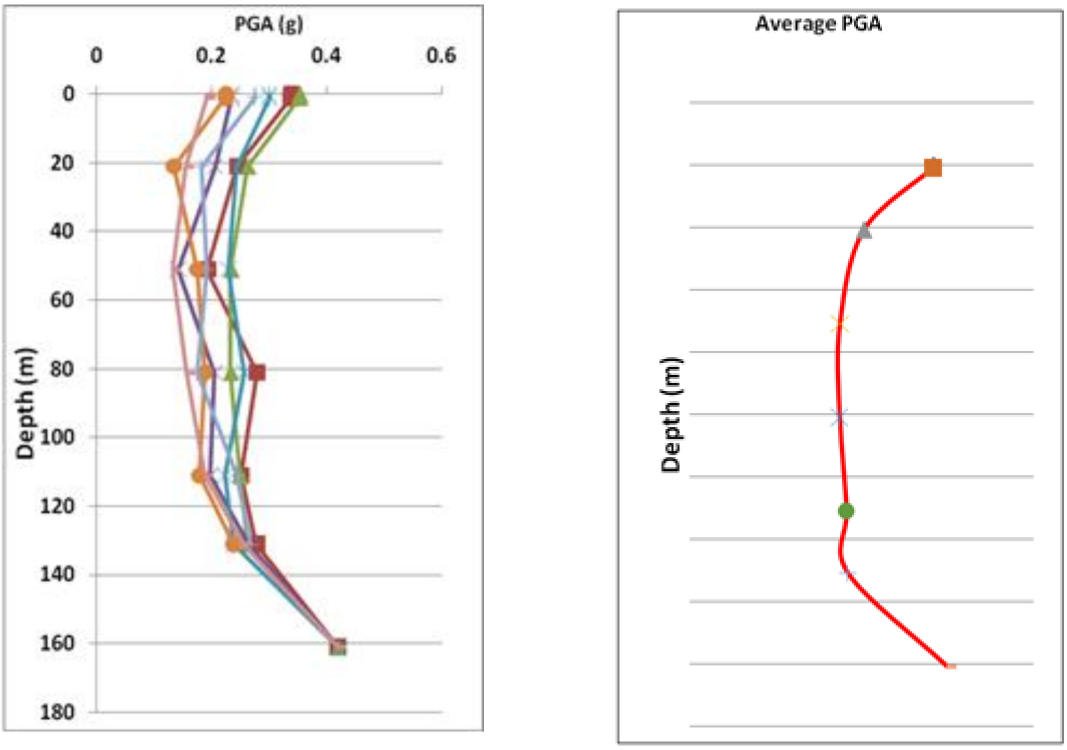

Figure 30: Site amplification for 475 Years

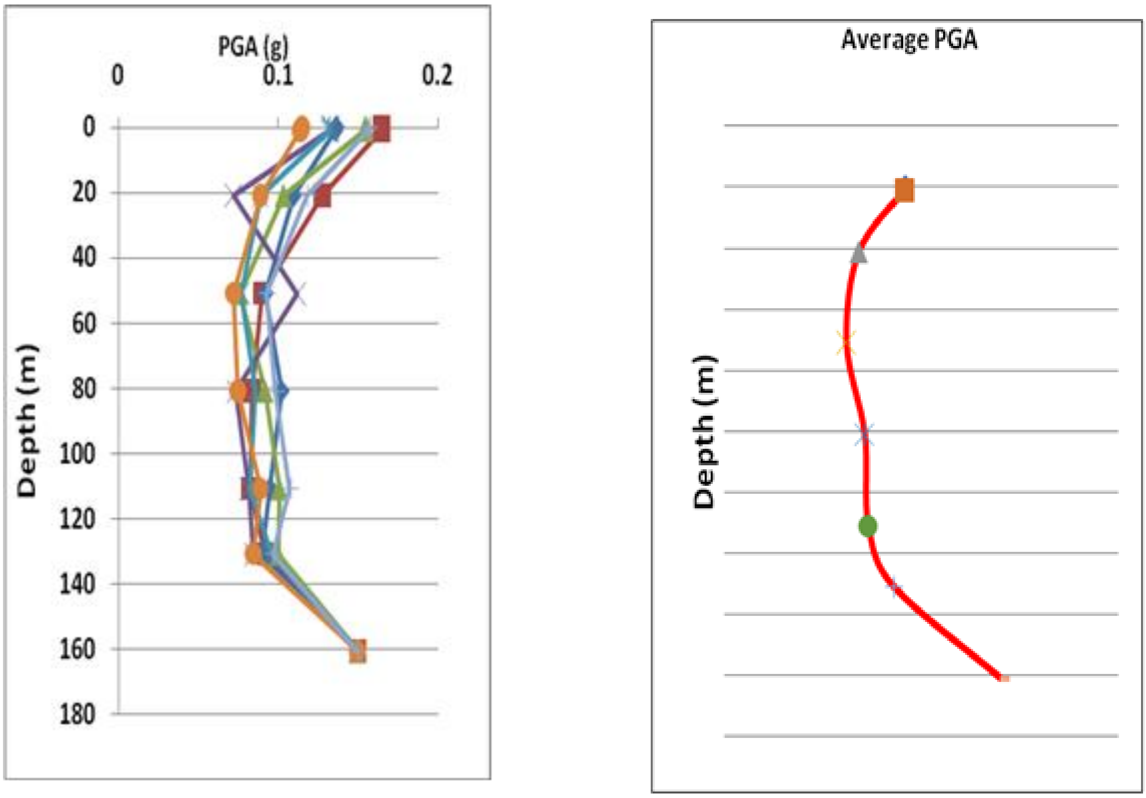

Figure 31: Site amplification for 10,000 years

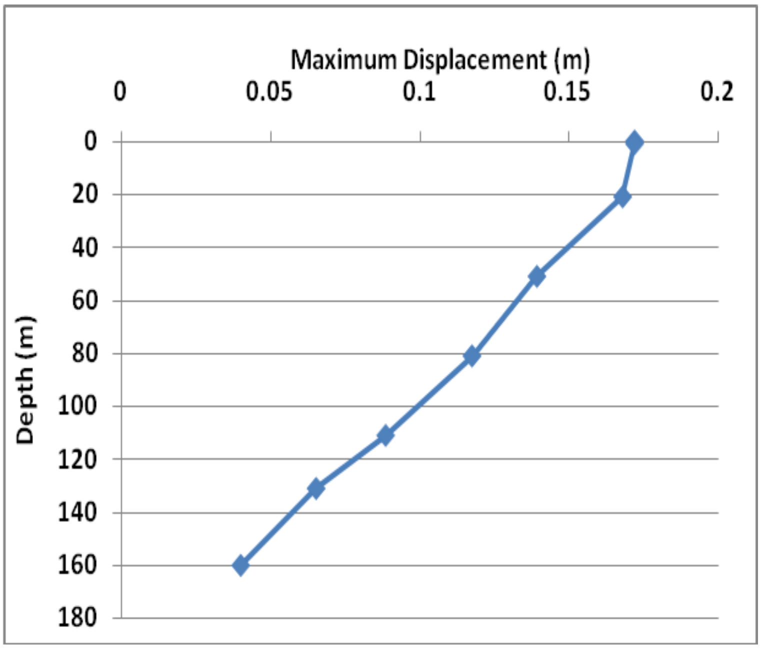

Figure 32: Displacement throughout soil profile for 10,000 years

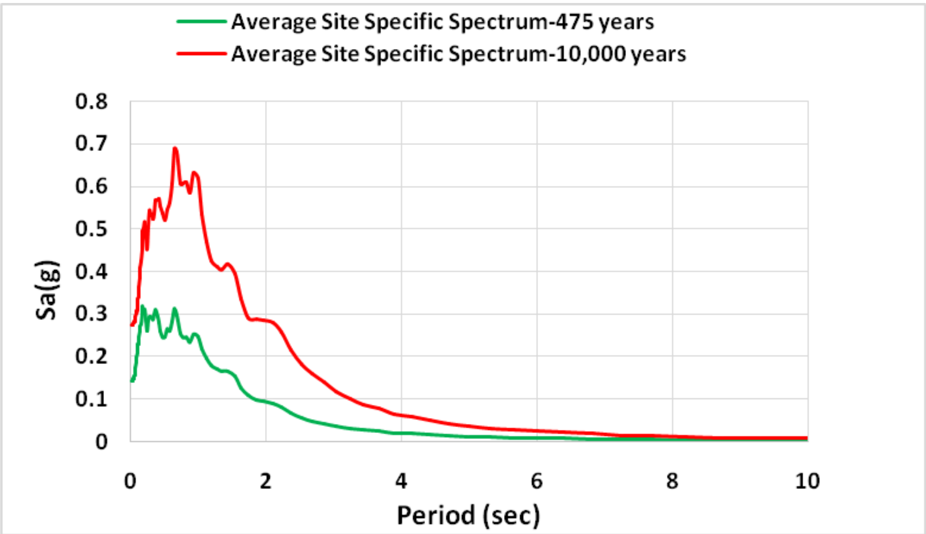

Figure 33: Average site-specific response spectra for 475 and 10,000 years return periods

CHAPTER 5

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusions

During this study, a comprehensive PSHA was conducted to determine the design ground motions at the bedrock level and to incorporate the site response effects to determine the peak ground acceleration at the surface for Thal Doab area. A region specific seismic source characterization model for an area of 280,000Km^2 was developed using the seismotectonic database and knowledge collected through literature review. The seismotectonic model includes nine (9) area source zones. A composite catalogue was developed for the region.

The PSHA results have shown that:

- For 475 years of return period (10% of probability of exceedance in 50 years) the PGA is equal 0.15g at the bedrock level.
- For 10,000 years of return period (1% of probability of exceedance in 100 years), PGA is found to be equal to 0.42g at the bedrock.
- The PSHA analysis was not conducted for the surface Vs30 value because the surface soils may have been removed during the excavation for the foundation. Instead, the engineering bedrock is defined as the stiffest soil that was reached in geotechnical boreholes at 150 m and the analysis were conducted at the bedrock level/engineering rock conditions.
- Taking into account the site response analysis, for 475 years return period calculations, the bedrock PGA is slightly amplified at the surface due to the decrease in the stiffness of the surface soils. The PGA at the surface is

estimated as 0.14g in average, but higher values are observed for different individual ground motions.

- The site response analysiss showed that PGA at the bedrock (PGA=0.42g) (150m depth) is de-amplified at the surface, resulting in high soil deformation due to the modulus degradation and the damping increase in the soft surface soils. The de-amplification is found to be significant, the estimated PGA is 0.27g at the ground surface.

5.2 Recommendations

- The de-amplification resulted in 0.18 meter horizontal displacement at surface level for free field conditions. The displacement may vary when the soil is loaded with the structure, therefore Seismic Soil Structure Interaction (SSI) Analysis is recommended.
- As water is not modeled in the study and due to shown deformation in the soil water/pore water pressure behavior is required to be analyzed on more updated basis through liquefaction potential assessment with site response analysis.

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