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Updated Probabilistic Seismic Hazard Assessment of Pakistan

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Abstract

Probabilistic seismic hazard assessment of Pakistan is carried out to compute hazard in terms of peak ground acceleration (PGA) and spectral acceleration (SA) for 975 and 2475 years return periods. A composite earthquake catalogue consisting of 32,700 events has been compiled having a magnitude range of M_w 4.0-8.2 in this study and used in the analysis to make computations at a rectangular grid of 5 km in the OpenQuake platform. Ground motion values have been obtained for flat rock reference seismic site conditions with shear wave velocity of 760 m/s. The epistemic uncertainties inherent in ground motion prediction equations and maximum magnitude potential of seismic sources are taken into account through logic tree. Ground motion prediction equations are assigned equal weights in the logic tree while different various weight are assigned to the maximum magnitude potential models. Results of the study are expressed as ground motion contour maps, mean uniform hazard spectra for important cities in Pakistan. PGA ranges from 0.16 to 0.54g for 10 % of probability of exceedance, 0.23 to 0.72g of probability of exceedance 0.32 to 1.02 g for 2 % of probability of exceedance in 50 years. Spectral acceleration at 0.2 s range from 0.67 to 2.19g for 2% chance of exceedance in 50 years, respectively. While spectral acceleration at 1.0 s values range from 0.09 to 0.52g 2% chance of exceedance in 50 years. Comparison of results of this study with other well regarded references of suggest that results of the study are rational and are reliable.

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1. Introduction

Pakistan is located at the intersection of the Indian, Eurasian and Arabian major tectonic plates and due to their interaction with each other earthquakes are very frequent in Pakistan. Earthquakes have caused wide spread damage in Pakistan and it has history deadliest earthquakes. Kashmir earthquake (2005), Dalbadine (2011), Awaran (2013) and Hindukush earthquake (2015) are the recent earthquakes occurred in this region having M_w greater than 7.0 that have caused damages and resulted losses in the country. These earthquakes constantly poses threat to lives and infrastructure as they may take place due to tectonic setting of Pakistan. Together with high hazard, seismic vulnerability of structures is also very high making seismic risk is also high in Pakistan. Tectonic setting of Pakistan is unique due to presence convergence plate boundaries of three major plates. Indian plate that is located in north of Pakistan and moving at velocity of 20.5 mm/ year with respect to the Eurasian plate (Ader et al., 2012). While, Arabian plate located in the south west of Pakistan is colliding with the Eurasian plate and as results of their interaction Makran Subduction Zone is formed. Arabian plate is subducting under the Eurasian plate at a velocity of 33 mm/ year (Apel et al., 2006). Makran earthquake (1945) which caused tsunami occurred in the subduction region. Due to interaction of plates some important and unique tectonic features have been developed. Hindukush-Pamir, Himalayas, Makran and Kirther and Suleiman ranges are some examples of these features which warrant careful assessment of seismic hazard as these tectonic features can act potential source of generating future earthquakes that can cause wide spread damage and destruction. The geological map of Pakistan is shown in Figure 1.

In the literature concerning Pakistan there are good number of studies on seismic hazard analysis. Among these, Rahman et al. (2021) is the most recent. Rahman et al. (2021) is based on hybrid approach consisting of spatial smoothen approach and the classical approach and it predicts high hazard value PGA in range of 0.0-0.70g.

This study is entirely based on application of Cornell (1968) and McGuire (1976) approach implemented in the OpenQuake engine. In the Cornell- McGuire (1968-1976) also known as classical approach area polygons are used as sources and the seismicity characteristics within these sources are assumed uniformly distributed. The classical procedure is adopted for study because of probabilistic seismic hazard assessment approach is suitable for region where fault are not very well characterized and coverage of earthquake data in time is limited. Geological information is combined with earthquake data to delineate the seismic source model. This all is valid for the case of Pakistan and therefore Cornell-McGuire (1968-1976) approach is the fundamental and suitable approach for probabilistic seismic hazard assessment for Pakistan. Probabilistic seismic hazard assessment approach is carried out on the basis of: (1) earthquake catalogue (2) source model (3) ground motion prediction equations (4) numerical calculator.

Figure 1: Tectonic map of Pakistan (Geological survey of Pakistan)

A flow chart of probabilistic seismic hazard assessment methodology followed in this study is shown in Figure 3.

Figure 2: Probabilistic seismic hazard assessment scheme

1. Earthquake Catalogue

Earthquake catalogue in the probabilistic seismic hazard assessment (PSHA) is pivotal and its compilation is the starting point of PSHA. A reliable and complete catalogue guarantees in obtaining reliable seismic hazard results. Ideally, the earthquake catalogue should report all earthquakes which had taken place in region under investigation that is why earthquake catalogue is always composite (having contributions from different sources) and homogenized. All those earthquake events that would affect the study area under investigation should be reported in catalogue. This problem is encountered at the boundaries of the study area. Therefore, all the events that have occurred at least 200 kilometres (km) from boundary of the study area should be considered in the computation of seismic hazard.

Earthquake catalogue for Pakistan has resources available for compilation and also for updating the existing catalogue. These includes Zare et al. (2014), Waseem et al. (2018) and Khan et al. (2018) studies. Zare et al. (2014) compiled earthquake catalogue for Middle East Region under the project Earthquake Model of Middle East Region (EMME) and it includes Pakistan region in its coverage as well and this catalogue is complete up to 2006. Waseem et al. (2018) also presents catalogue but restricted to the northern Pakistan region. Recently, earthquake catalogue has been compiled for Pakistan by Khan et al. (2018) and subsequently used in probabilistic seismic hazard analysis (PSHA) of Pakistan by Waseem et al. (2020). Khan et al. (2018) covers comprehensively historical period earthquakes and earthquakes in the modern Instrumental period. This catalogue has moment magnitude coverage of 4.0-8.3 and geographical coverage of 20-40° E and 40-83° N. Khan et al. (2018) catalogue is complete up to 2016 is updated for new earthquakes from the online databanks. Online databanks of International Seismological Centre (ISC), National Earthquake Information Centre (NEIC), United States Geological Survey (USGS), International Institute of Earthquake Engineering and Engineering Seismology (IIEES) and European Mediterranean Seismological Centre (EMSC) are considered for updation. In the updation 23,798 events are added in the catalogue as stock from 2016 onwards.

Total number of events in this earthquake catalogue are 32,700. This catalogue is further divided into two sub catalogues: (1) Shallow source catalogue (2) Deep source catalogue, in order to delineate the shallow and deep source zones in the source model. Earthquake events up to 50km deep were considered as shallow earthquakes and earthquake events having focal depth greater than 50km were considered as part of the deep earthquake catalogue. These two sub- catalogues were used in delineation of the source models in the study area.

Figure 3: Compiled earthquake catalogue (a) shallow earthquake catalogue (b) deep earthquake catalogue

2. Source Model

In the Cornell-McGuire (1968-1976) approach the source model is important component and it may be defined by combining the seismicity and local geological information. Tectonics of Pakistan is dominated by Himalayas thrust belt, Karakorum, Makran, Suleiman and Kirther mountain ranges. But, faults along which earthquakes occur are not well characterized in Pakistan with few exceptions such as Chaman fault system located in south west of Pakistan. In this context Cornell (1968-1976) approach is very attractive and most appropriate for computing the hazard concerning Pakistan. One of the advantages of the Cornell-McGuire (1968-1976) approach is it application in regions for which earthquake data is limited geological information maybe combined to define sources. There are different sources models used for Pakistan in the literature. The most recent studies are Waseem et al. (2020) and Sesetyan et al. (2018). These studies are also consulted, while defining the source model.

In this approach, seismicity parameters are uniformly distributed with the zones and there is a change in seismicity (hence the hazard) at the boundaries of zones. User subjectivity is also present in the definition of source model.

The study region is divided into forty-four area source polygons consisting of interface subduction, intraslab subduction, deep seismicity and shallow active regions. Zone 31, 32, 38 are interface subduction, 40, 41, 42, 43 are deep seismicity and rest are active shallow zones as illustrated in Figures 6 and 7.

Figure 4: Shallow seismic source zones

Figure 5: Deep seismic source zones

3. Processing of Earthquake Catalogue

3.1 Declustering and completeness analysis

Compiled earthquake catalogue has to be subjected to declustering and completeness analysis checks before usage in the analysis. These are essential checks applicable in the Cornell-McGuire (1968; 1976) approach. Earthquake catalogue events consisting of main shocks can only be considered for carrying out analysis, therefore dependent events should be eliminated from the catalogue known as declustering process. Earthquake process is assumed as poissonian process (i.e., all events in the process are independent). Therefore, earthquake catalogue is brought consistent with this assumption and in order to meet this requirement declustering algorithm is needed. Although such algorithm developed locally is not available therefore it has been adopted. Gardner and Knopoff (1974) algorithm is selected and used in this study. Gardner and Knopoff (1974) is selected because it is most frequently adopted algorithm in world and all of the previous seismic hazard studies carried out for the Pakistan also used it. This algorithm includes windowing procedure in time and space depending on the magnitude of main event to identify the main shocks and the depending events. This task is performed in the ZMAP (Weimer, 2001) software. After the declustering check 6,638 events were in the catalogue and the same is used for developing the recurrence relationships for the seismic source zones of the study area. Declustered catalogue divided into (1) shallow and (2) deep catalogues is shown in Figure 8.

(a)

(b)

Figure 6: Plot of the de-clustered catalogue (a) shallow events (b) deep events

Earthquake catalogue is never complete for small magnitude earthquakes, as they may have gone undetected in record of catalogue. Earthquake catalogue may not be reporting them in the historical and early instrumental periods. Therefore, it is very essential to perform completeness check for the catalogue. After performing the declustering check, catalogue is subjected to the completeness analysis. This analysis is mostly performed by dividing the earthquake magnitude values into 0.5 or a smaller unit range groups e.g (4.0, 4.5, 5.0, 5.5 and etc) and for each magnitude range completeness periods are reported.

Completeness analysis is carried out at first using Mulgaria and Tinti (1985) procedure. But due to the subjectivity involved in the method, Stepp (1973) procedure has been adopted. Initially, catalogue was divided into 0.5 bin units and completeness periods were obtained and hazard analysis was carried out. But, later on, completeness analysis was revised using 0.25 magnitude bin size and results thus obtained were considered appropriate. Completeness periods thus obtained were used for defining the magnitude frequency distribution for each seismic zone. Completeness analysis results using Stepp (1973) procedure with magnitude bin size of 0.25 units are shown in Figure 9.

Figure 7: Completeness analysis for different magnitude ranges: (a) 4.0-4.25 (b) 4.25-4.50 (c) 4.50-4.75 (d) 4.75-5.00 (e) 5.00-5.25 (f) 5.25-5.50 (g) 5.50-6.00 (h) 6.00-6.25 (i) 6.25-6.50 (j) 6.50-6.75 (k) 6.75-7.00 (l) ≥ 7.00

Table 1 Completeness periods for earthquake magnitude ranges in catalogue

S.No	Magnitude range	Completeness periods
1	4.00≤M _w <4.25	2000-2020
2	4.25≤M _w <4.50	2000-2020
3	4.50≤M _w <4.75	1980-2020
4	4.75≤M _w <5.00	1980-2020
5	5.00≤M _w <5.25	1980-2020
6	5.25≤M _w <5.50	1980-2020
7	5.50≤M _w <5.75	1980-2020
8	5.75≤M _w <6.00	1970-2020
9	6.00≤M _w <6.25	1920-2020
10	6.25≤M _w <6.50	1920-2020
11	6.50≤M _w <6.75	1920-2020
12	6.75≤M _w <7.00	1900-2020
13	7.00>=M _w	1890-2020

4. Earthquake Recurrence Relationships

Earthquake recurrence relationships for seismic sources is defined by the Gutenberg and Richter (1956) relationships. Gutenberg and Richter relationships are derived between the cumulative magnitude and the corresponding activity rates by regression analysis technique. Using the processed earthquake data present within each source, least square regression analysis method is used to obtain the parameters of the Gutenberg and Richter (1956) recurrence law. Since, the standard Gutenberg-Richter (G-R) recurrence law covers infinite range of magnitude range, bounded Gutenberg-Richter law is be defined (The standard laws will be truncated at the maximum and minimum magnitude values present in the source).

Bounded G-R recurrence relationship for magnitude is adopted on the basis of the completeness periods calculated for different magnitude ranges. Bounded G-R recurrence law is given by following mathematically equation:

$$\lambda_M = \lambda_0 \cdot \frac{e^{-\beta \cdot (M_w - M_w^{\max})}}{1 - e^{-\beta \cdot (M_w^{\max} - M_w^{\min})}}$$

Where, $\lambda_0 = v_o(\alpha - \beta M_w)$ and $M_w^{\min}$ and $M_w^{\max}$ are the lower magnitude value and maximum magnitude potential of seismic zones. α and β are 2.303a and 2.303b, "a" and "b" are Gutenberg and Richter parameters obtained by regression analysis.

Gutenberg and Richter parameters were computed first using magnitude bins of 0.50 units but were re-computed using 0.25 magnitude bin size. Parameters obtained using magnitude bin 0.25 were considered most relevant and appropriate for use in analysis.

Maximum likelihood method of Weichert (1980) and least square regression methods were used to compute Gutenberg and Richter parameters. Computation made using maximum likelihood procedure and by least square did not differ much. In this study, least square regression is used on the earthquake data for each source to establish the recurrence law. Gutenberg-Richter relationships for all source zones are shown in Figure 10 and characteristics of zones including the Gutenberg-Richter parameters are tabulated in Table 2. In Table 3 Gutenberg and Richter parameters computed using Mulagria and Tinti (1985) are reported respectively. In appendix-I of the paper Gutenberg-Richter plots are shown.

Table 2 Gutenberg-Richter (G-R) parameters using Stepp (1973) procedure

SSZ	No of events	a-value	b-value	Mmin	Mmax1	Mmax2	Mmax3	N	Depth (km)
1	131	4.34	0.90	4.00	7.00	7.30	7.60	5.32	17.80
2	96	5.32	1.13	4.10	6.30	6.60	6.90	4.96	21.00
3	85	4.11	0.91	4.00	8.20	8.50	8.80	3.01	14.40
4	153	5.31	1.10	4.10	7.00	7.30	7.60	6.51	20.70
5	210	4.72	0.94	4.00	7.10	7.40	7.70	8.80	15.60
6	245	4.83	1.01	4.00	8.50	8.80	9.10	6.35	18.00
7	89	4.57	1.05	4.00	6.50	6.80	7.10	2.40	15.60
8	174	4.08	0.85	4.00	7.50	7.80	8.10	4.79	14.40
9	58	3.03	0.70	4.00	7.40	7.70	8.00	1.71	18.40
10	15	2.29	0.73	4.00	5.70	6.00	6.30	0.24	13.70
11	131	4.61	0.95	4.10	7.70	8.00	8.30	5.02	19.50
12	128	5.11	1.05	4.00	6.40	6.70	7.00	8.10	17.10
13	19	2.76	0.74	4.00	6.40	6.70	7.00	0.61	24.00
14	65	4.31	0.94	4.10	7.50	7.80	8.10	2.97	15.30
15	52	3.74	0.88	4.10	7.50	7.80	8.10	1.34	16.60
16	393	4.71	0.88	4.00	7.50	7.80	8.10	15.50	20.90
17	35	3.79	0.92	4.00	6.80	7.10	7.40	1.32	14.50
18	82	4.09	0.90	4.00	7.00	7.30	7.60	3.02	12.70
19	36	3.61	0.83	4.00	6.60	6.90	7.20	1.87	21.60
20	129	4.44	0.93	4.00	7.70	8.00	8.30	5.05	16.90
21	412	5.48	1.04	4.00	7.30	7.60	7.90	21.10	16.10
22	60	5.11	1.11	4.00	6.40	6.70	7.00	4.51	13.00
23	105	3.83	0.80	4.00	7.40	7.70	8.00	4.27	17.70
24	475	6.03	1.13	4.00	7.70	8.00	8.30	32.40	18.80
25	222	4.30	0.84	4.00	7.60	7.90	8.20	8.61	17.30
26	384	5.11	0.97	4.00	7.30	7.60	7.90	17.19	18.50
27	53	4.30	0.98	4.10	6.10	6.40	6.70	1.97	19.40
28	35	3.09	0.75	4.00	6.10	6.40	6.70	1.19	27.10
29	111	5.91	1.25	4.00	6.80	7.10	7.40	8.29	21.50
30	131	4.87	1.01	4.00	8.20	8.50	8.80	6.77	18.00
31	110	4.43	0.95	4.10	8.20	8.50	8.80	3.44	19.40
32	165	4.59	0.93	4.00	7.90	8.20	8.50	7.51	18.70
33	114	3.73	0.79	4.00	7.50	7.80	8.10	3.84	18.00
34	50	3.63	0.83	4.00	6.90	7.20	7.50	2.04	15.80
35	61	3.72	0.84	4.00	7.50	7.80	8.10	2.34	14.20
36	58	3.93	0.86	4.00	6.50	6.80	7.10	3.00	16.10
37	282	4.24	0.83	4.00	8.00	8.30	8.60	8.09	17.20
38	18	3.07	0.80	4.10	5.80	6.10	6.40	0.65	18.10
39	261	4.99	0.98	4.00	6.90	7.20	7.50	12.35	18.50
40	627	4.69	0.84	4.00	7.90	8.20	8.50	21.38	134.10
41	122	4.87	1.04	4.10	6.70	7.00	7.30	3.88	112.50
42	71	3.19	0.74	4.00	6.50	6.80	7.10	1.70	101.10
43	76	3.50	0.81	4.10	6.70	7.00	7.30	1.56	92.80
44	54	3.01	0.69	4.10	7.50	7.80	8.10	1.49	87.30

Table 3 Gutenberg-Richter (G-R) parameters using Mulagria and Tinti (1985) procedure

SSZ	No of events	a-value	b-value	Mmin	Mmax1	Mmax2	Mmax3	N	Depth (km)
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4	153	5.04	1.02	4.10	7.00	7.30	7.60	6.51	20.70
5	210	4.76	0.96	4.00	7.10	7.40	7.70	8.80	15.60
6	245	4.36	0.85	4.00	8.50	8.80	9.10	6.35	18.00
7	89	4.73	1.03	4.00	6.50	6.80	7.10	2.40	15.60
8	174	4.35	0.90	4.00	7.50	7.80	8.10	4.79	14.40
9	58	2.95	0.68	4.00	7.40	7.70	8.00	1.71	18.40
10	15	2.49	0.75	4.00	5.70	6.00	6.30	0.24	13.70
11	131	3.72	0.76	4.10	7.70	8.00	8.30	5.02	19.50
12	128	4.56	0.94	4.00	6.40	6.70	7.00	8.10	17.10
13	19	2.75	0.74	4.00	6.40	6.70	7.00	0.61	24.00
14	65	4.18	0.91	4.10	7.50	7.80	8.10	2.97	15.30
15	52	4.01	0.92	4.10	7.50	7.80	8.10	1.34	16.60
16	393	4.72	0.88	4.00	7.50	7.80	8.10	15.50	20.90
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23	105	4.06	0.85	4.00	7.40	7.70	8.00	4.27	17.70
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25	222	3.97	0.77	4.00	7.60	7.90	8.20	8.61	17.30
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29	111	3.99	0.84	4.00	6.80	7.10	7.40	8.29	21.50
30	131	4.60	0.96	4.00	8.20	8.50	8.80	6.77	18.00
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33	114	3.54	0.74	4.00	7.50	7.80	8.10	3.84	18.00
34	50	3.74	0.86	4.00	6.90	7.20	7.50	2.04	15.80
35	61	3.23	0.73	4.00	7.50	7.80	8.10	2.34	14.20
36	58	2.99	0.68	4.00	6.50	6.80	7.10	3.00	16.10
37	282	4.34	0.83	4.00	8.00	8.30	8.60	8.09	17.20
38	18	3.05	0.88	4.10	5.80	6.10	6.40	0.65	18.10
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43	76	5.73	1.27	4.10	6.70	7.00	7.30	1.56	92.80
44	54	2.90	0.67	4.10	7.50	7.80	8.10	1.49	87.30

5. Maximum Magnitude

Maximum magnitude for sources is computed as per the approach of Sesetyan et al. (2018) for EMME project. Three different magnitude values are used as Mmax1 (Historical Seismicity), Mmax2 (Historical Seismicity + 0.3), Mmax3 (Historical Seismicity + 0.6). These maximum magnitude values i.e., Mmax1, Mmax2, Mmax3 are assigned 0.50, 0.30 and 0.10 weights in the logic tree.

6. Ground Motion Prediction Equations

Ground motion prediction equations are an integral part of any seismic hazard assessment scheme and they are used to estimate the ground motion parameters such as PGA and SA's for various spectral periods. Without, GMPEs probabilistic seismic hazard assessment (PSHA) and without GMPEs PSHA cannot be carried out. Robust, GMPEs developed on local data are still to be developed in Pakistan as ideally equations developed from local data are preferred for usage in PSHA. Although, Pakistan is one of the seismically very active regions of world and in the context of the GMPEs developed on local databank, Shah et al. (2012) is the only equation available in literature. But, due to inappropriate functional form and limitations on data over which it has been developed, it is suitable for usage in PSHA. GMPEs applied in the EMME region study (Sesetyan et al., 2018) has also used very small portion of strong motion data from Pakistan for evaluating the performance of GMPEs due to limitation on the data.

The most challenging part in PSHA is GMPEs adoption for the deep earthquakes of Hindukush region and these earthquakes represent deep crustal tectonic setting. In the case of Hindukush tectonic setting, GMPEs developed for subduction region for in-slab conditions can be applied. Similar practice is followed while computing seismic hazard assessment available in literature. In the knowledge of author, there is one study (Khan et al., 2021) in which testing of subduction GMPEs against time histories of Hindukush earthquakes recorded in Peshawar is underway. Preliminary outcome of this study suggested that time histories records are recorded in 300-400 km away from the sources. Near field data is not available due to absence of station in vicinity close to Hindukush region (Afghanistan). Testing of the far field data has revealed that none of subduction GMPEs are consistent with the Hindukush deep earthquakes. The candidate GMPEs pool for the study consists of Youngs et al. (1997); BC Hydro (2014); Lin and Lee (2008); Kanno et al. (2006).

Usage of inappropriate GMPEs in hazard studies can either result in the underestimation or overestimation of hazard. Shallow active regions exist in Pakistan and in literature one study is available on testing of global GMPEs in Pakistan.

In Makran subduction regions GMPEs of Line and Lee (2008) and of Youngs et al. (1997) are used and similarly for deep crustal earthquakes region of Hindukush and Himalayans in-slab subduction version of the Lin and Lee (2008) and of the Youngs et al. (1997) are used. For the shallow active region GMPE of Akkar et al. (2014) and Cauzzi et al. (2015) are considered for modelling the ground motions of earthquakes. Main reason behind selecting and using these GMPEs is they are well established and used worldwide. The relevant tectonic setting of Pakistan is consistent with the regions, these GMPEs are derived.

7. Hazard Computations

7.1 Logic Tree

Epistemic uncertainties are inherent due to lack of knowledge of modelling process. Due to lack of knowledge of earthquake process these uncertainties are handles through the logic tree. Each branch on the logic tree represents a decision steps and sum of all factor is unity on every logic tree branch (Figure 11)

Logic tree has been used for seismic source model, declustering algorithm and the ground motion prediction equations. In this study, epistemic uncertainties in assigning maximum magnitude potential and in ground motion prediction equations is considered.

Two GMPEs used for the shallow and deep zones are assigned equal 50% weights, as they are assumed equally applicable for the region.

Figure 8: Logic tree

7.2 Calculation Engine

Probabilistic seismic hazard is generating numerical simulations of all possible ground motion scenarios. Probabilistic seismic hazard assessment approach not only considers uncertainties in earthquake location and its magnitude value but also takes into account variation in the ground motion using the probability density functions. It requires a calculator or engine to carry out the analysis and it is impossible to process the data manually. OpenQuake engine (Pagani et al., 2014), an open source application for seismic hazard and risk assessment has been used to perform analysis.

8. Results

The outcomes of the study are contour ground motion maps and uniform hazard spectra. Contour maps are generated for PGA and SA's for 95, 475, 975, 2475 years return periods. Spectral acceleration maps are generated for 0.2 and 1.0 seconds. PGA values range from 0.07 to 0.25g (for 41% chance of exceedance in 50 years) shown in Figure 12, 0.16 to 0.54g (for 10% chance of exceedance in 50 years) shown in Figure 13, 0.23 to 0.72g (for 5% chance of exceedance in 50 years) and 0.32 to 1.02g (for 2% chance of exceedance in 50 years) shown in Figure 14-15 respectively. The SA values at 0.2s range from 0.46 to 1.51g (for 5% chance of exceedance in 50 years) shown in Figure 18 and 0.67 to 2.19g for 2% chance of exceedance in 50 years, respectively shown in Figures 19. While the SA 1.0 values range from 0.06 to 0.36g and 0.09 to 0.52g respectively for 5%, 2% chance of exceedance in 50 years shown in Figures 20-23. Uniform hazard spectra for 975 and 2475 years return period for eight cities in Pakistan are also shown in Figure 24.

Figure 9: Mean peak ground acceleration map for 41 % of exceedance in 50 years

Figure 10: Mean peak ground acceleration map for 10 % of probability exceedance in 50 years

Figure 11: Mean peak ground acceleration map for 5 % of probability of exceedance in 50 years

Figure 12: Mean peak ground acceleration map for the 2 % of probability of exceedance in 50 years

Figure 13: Mean spectral acceleration (0.2 s) map for 41 % of probability of exceedance in 50 years

Figure 14: Mean spectral acceleration (0.2 s) map for 10 % of probability of exceedance in 50 years

Figure 15: Mean spectral acceleration (0.2 s) map for 5 % or probability of exceedance in 50 years

Figure 16: Mean spectral acceleration (0.2 s) map for 2 % or probability of exceedance in 50 years

Figure 18: Mean Spectral acceleration (1.0 s period) map for 2 % or probability of exceedance in 50 years

Figure 19: Mean 5% damped uniform hazard spectra for important cities

9. Comparison with similar studies

Ground motion values obtained in this study are compared with other regional studies. Four studies are selected for this purpose: (1) Sesetyan et al. (2018) (2) Rahman et al. (2021) (3) BCP (2007) and (4) Pakistan Meteorological Department and Norwegian Seismic Array, 2007 (PMD and NORSAR, 2007). Sesetyan et al. (2018) reports PGA values for 475 and 2475 years return periods. Rahman et al. (2021) produced peak ground parameters for 475 and 2475 years return periods for PGA and SA's at 0.1 and 0.2 seconds. BCP (2007) refers to the PGA values corresponding to 475 years return period. Both of these studies represents PGA values for engineering bedrock sites. BCP (2007) study was produced as results of revision of the seismic provisions. While, Sesetyan et al. (2018) study was carried out for the Middle East-Caucasus region including Pakistan. These studies have used different ground motion prediction equations and different sources models. Regional study of EMME (Sesetyan et al., 2018) used both fault and area sources in their source model. Rahman et al. (2021) used Cornell's (1968) and spatially smoothed gridded seismicity model using 110 crustal faults. PMD and NORSAR (2007) produced seismic hazard maps for both PGA and SA for 0.2, 0.5, 1.0 and 2.0 periods for 50, 100, 500 and 1000 years return periods. PMD and NORSAR study made use of the Cornell (1968) approach using area sources. Ground motion values for the return period of 475 years return period in this study are compared with these three studies, as illustrated in Figures 25, 26, 27 and 28 respectively.

(a)

(b)

Figure 20: Comparison of (a) Sesetyan et al. (2018) (b) Current study

(a)

(b)

Figure 21: Comparison of (a) Rahman et al. (2021) (b) Current study

(a)

(b)

Figure 22: Comparison of (a) BCP (2007) (b) Current study

(a)

(b)

Figure 23: Comparison of (a) PMD and NORSAR (2007) (b) Current study

Sesetyan et al. (2018) included in here predicts PGA value for flat engineering bedrock site condition conforming to 800m/s while the current study is predicting PGA value for 760m/s for flat rock site conditions. The two studies can be compared and their comparison show that ground motion values are in the similar range (Figure (23)). Sesetyan et al. (2018) predict PGA value for Pakistan in range of 0.04-0.59g while this study predict 0.16-0.54 g. Geographic distribution of the ground motion intensity for both studies is almost similar indicating the current results are compatible with the Sesetyan et al. (2018). Sesetyan et al. (2018) results slightly differs from current study for the reason there is slight difference in the results of current and Sesetyan et al. (2018). Rahman et al. (2021) produced seismic hazard map for PGA suggest slightly higher distribution of ground motion. Maximum PGA value suggested by Rahman et al. (2021) is 0.00-0.70 g compared to corresponding value of 0.08-0.54 g in current study. Area sources and smoothed seismicity approaches have been used in the analysis. Geographical distribution PGA values in Rahman et al. (2021) are higher compared to current study (i.e., 0.40-0.50 g). Completeness analysis adopted method in Rahman et al. (2021) is not explicitly mentioned and b-value for most of area sources are less than 1.0. These are the major observations noted in Rahman et al. (2021). PGA corresponding to a return period of 475 years in Rahman et al. (2021) at important cities is in agreement with the current study except at Chitral city. At Chitral Rahman et al. (2021) predicts 0.20-0.30 g whereas all other studies predicts on higher side to Rahman et al. (2021).

Seismic hazard map of the BCP (2007) compared to current study shows BCP (2007) is predicting slightly lower PGA values (Figure 27). BCP (2007) seismic hazard map predicts PGA in range of 0.05-0.32 g and the upper bound on the PGA level is not mentioned. Geographically distribution of PGA values obtained in this study in the similar range is on the higher side compared to the BCP (2007). PMD and NORSAR (2007) PGA values ranges from 0.00-1.20 g (Rahman et al., 2021) which represents a very high value. Comparison of ground motion values in current study at eight important cities in Pakistan with the BCP (2007), Sesetyan et al. (2018), Rahman et al. (2021) and PMD and NORSAR (2007) is shown in Table 5. Although the cities comparison is suggesting PMD and NORSAR (2007) Sesetyan et al. (2018) and current studies are correlating very well. But, PMD and NORSAR (2007) predicts very high values (i.e., 0.00-1.20 g) and due to this fact it is comparable with current study The ground motion values in the current study are in agreement with the well-established and accepted study of Earthquake Model of Middle East (EMME) Region.

Table 4 Comparison of the studies

S.No	City	Current study	BCP (2007)	PMD and NORSAR (2007)	Sesetyan et al. (2018)	Rahman et al. (2021)
1	Islamabad	0.46 g	0.16-0.24 g	0.37 g	0.44 g	0.45 g
2	Karachi	0.25 g	0.16-0.24 g	0.14 g	0.22 g	0.30 g
3	Lahore	0.23 g	0.08-0.16 g	0.25 g	0.18 g	0.29 g
4	Peshawar	0.43 g	0.16-0.24 g	0.36 g	0.33 g	0.41 g
5	Quetta	0.41 g	0.24-0.32 g	0.39 g	0.31 g	0.35 g
6	Hyderabad	0.19 g	0.08-0.16 g	~0.15 g	0.15 g	0.10-0.20 g
7	Chitral	0.42 g	> 0.32 g	~ 0.40 g	0.57 g	0.20-30 g
8	Muzzaffarabad	0.42 g	> 0.32 g	0.44 g	0.43 g	> 0.475 g

10. Conclusions

An updated seismic hazard definition of Pakistan is made available that defines seismic hazard in terms of PGA and SA for 95, 475, 975, 2475 years return periods. PGA in Pakistan varies in the range 0.16-0.54 g corresponding to 475 years return period and 0.32-1.02g for return period of 2475 years. Results of the study can be readily used in the seismic risk assessment component for hazard and seismic risk assessment studies.

The following are conclusions drawn from the study:

1. There are three seismo-tectonic settings identified in Pakistan: (1) shallow active regions (2) interface and intraslab subduction (3) deep crustal seismicity
2. Strong motion data in Pakistan is limited and a local, state of art ground motion prediction equation is yet to be developed. As such these GMPEs were adopted for seismic active regions of the world having similar tectonics to Pakistan.
3. Strong ground motion records of deep earthquakes are available, but for only in far fields.
4. Comparison of results of this study with BCP (2007) shows that BCP (2007) study indicates somewhat lower hazard values.
5. Results of the study are in agreement with well accepted regional hazard studies. They also indicate that seismic hazard is comparatively high in Pakistan. The north western and north eastern part of Pakistan is located in region where higher ground motions are expected. Similarly, south eastern region where Gawdar

port is situated, expected ground motion are also higher. Maximum range of hazard corresponding to the return period of 475 years in is observed in central Pakistan.

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Appendix-I