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Probabilistic Seismic Hazard Assessment of Pakistan

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Abstract

An updated probabilistic seismic hazard assessment (PSHA) of Pakistan is performed using the procedures developed for the US national seismic hazard maps and Earthquake model of the Middle East (EMME14). An updated earthquake catalogue is compiled using data from multiple databases. The background seismicity of the study area is modeled using the area source zones and the spatially smoothed gridded seismicity method, whereas a total of 110 crustal faults are explicitly modeled using their geological slip rates for estimation of their occurrence rate. Several ground motion prediction equations (GMPEs) of the Next Generation Attenuation relationships (NGA) are employed to estimate the hazard at bedrock level. The logic tree procedure is used to deal with the epistemic uncertainties in the source model. The maps for peak ground acceleration (PGA) and spectral accelerations (SA) at 0.2s, 1s and 2s natural period are developed for 10% and 2% probability of exceedance in 50 years. The final hazard maps shows relatively higher hazard values throughout the country as compared to the previous studies. The results can be used for structural design and assessment of new and existing structures and the improved basis for disaster risk reduction policies.

Keywords: Pakistan, Seismic hazard maps, Peak ground acceleration

1 Introduction

Pakistan is situated in a seismically active and earthquake prone region of the world. The country lies on the Himalayan orogenic belt in the northeast which is created by a slow collision between Eurasian and Indian plates spanning over the past 30-40 million years [1]. The seismotectonic environment of the country is very complex, which resulted into a complex network of active crustal faults (seismic sources) spread around the main plate boundary. Due to the complex geo-tectonic environment of the region, the country and its surrounding areas are posed to a higher level of seismic hazard. In the past, the country has been hit by several destructive earthquakes which has resulted into a huge number of fatalities. On the other hand the rapid growth in population and unsustainable urbanization had aggravated the seismic risk of the region. Adding insult to injury, the seismic hazard map of Pakistan as recommended and suggested by the building code of Pakistan [2] is older more than a decade. Therefore based on the latest information and improved approaches available, there is a dire need of an updated seismic hazard assessment (SHA) for the country.

In order to mitigate the seismic risk throughout the country, various efforts have been made in the past to estimate the likelihood of seismic ground shaking within Pakistan. The initial effort to conduct the seismic hazard assessment for Pakistan was made in 1986 for the Building code of Pakistan (1986) based on the instrumental earthquake catalogue (1905-1979 CE) [3]. According to this study Pakistan was divided into four seismic zones on the basis of Modified Mercalli Intensity scale (MMI) [4]. The second attempt was made by a well-known Global Seismic Hazard Assessment Program (GSHAP) [5-7]. These studies performed the probabilistic seismic hazard assessment of Pakistan under the umbrella of GSHAP. More than twenty seismic area sources were delineated for Pakistan and surrounded areas. The PGA map for a 10% probability of exceedance in 50 years was developed. The GSHAP study is the first ever study which proposed the seismic hazard maps for Pakistan in terms of PGA. After the devastating 8th October 2005 M_w 7.6 Kashmir earthquake, two studies were conducted. The first study was carried out by Pakistan Meteorological Department (PMD) in collaboration with Norwegian Seismic Array (NORSAR) [8]. The second study was conducted by National Engineering Services of Pakistan (NESPAK) [9] for development of seismic design provisions of Pakistan [2]. Hence the seismic hazard maps for Pakistan were developed that divided the whole territory in 5 zones (zone 1, zone 2A, zone 2B, zone 3 and zone 4) according to the Uniform Building Code UBC. All three of the above mentioned studies adopted the Cornell-McGuire approach to perform the probabilistic seismic hazard assessment for Pakistan. Zaman, Ornthammarath [10] and Ali [11] also conducted the probabilistic seismic hazard assessment of Pakistan. Zaman, Ornthammarath [10] adopted the US national seismic hazard maps (NSHMP) [12] procedure to develop hazard maps. Ali [11] used Cornel-McGuire approach to evaluate the seismic hazard assessment for Pakistan. The Earthquake Model of Middle East (EMME) [13] is the latest study that conducted the seismic hazard assessment of Pakistan.

2 Earthquake catalogue

In this study, a comprehensive and homogeneous earthquake catalogue of pre-historically reported (10 AD to 1900 CE), historical (1900 CE to 1964 CE) and instrumentally recorded (1964 CE to December 2018 CE) earthquake events are compiled using multiple databases. The compiled earthquake catalogue includes various international and local sources. The international sources include South Asian Catalogue (SACAT), the International Seismological Center (ISC) [14], National Earthquake Information Center (NEIC, USGS), Advanced National Seismic Center (ANSS) (U.S. Geological Survey, 2017), National Geophysical Data Center (NGDC) and Global Centroid Moment Tensor (GCMT). While the local sources include Pakistan Meteorological Department (PMD) and Water & Power Development Authority (WAPDA). The historical data are obtained from published literature (Quittmeyer and Jacob, 1979; Ambraseys, 2000; Ambraseys and Douglas, 2004; Ambraseys and Bilham, 2014; Zare et al., 2014; Khan et al., 2018). This latest earthquake catalogue is compiled for the Pakistan region that covers the geographical coordinates 20°– 40°N latitude and 58°– 83°E longitude.

Every database reports the earthquake events in different magnitude scale. Therefore, the compiled catalogue contains various magnitude scales. For example, USGS and ISC frequently report events in 20-s surface-wave magnitude (M_S), short-period P-wave magnitude (m_b), and moment magnitude (M_W), while PMD reports earthquake events in local magnitude (M_L), and GCMT catalogue commonly reports events in moment magnitude scale (M_W). For that reason, homogenizing the catalogue to a single representative magnitude scale is mandatory. This study uses moment magnitude as representative scale. In order to homogenize the magnitude, magnitude conversion equations were developed by carrying out the regression analysis for those events which are reported in two different magnitude scales including M_W as shown in Table 1.

The duplicated events reported by more than one source are removed from the compiled catalogue. The number of events reduced from 71759 to 34104 after eliminating duplicated events. The threshold magnitude selected is $M_W = 4$, because this is considered for engineering interest.

The main events were segregated from foreshocks and aftershocks, which are considered as statistically dependent events, commonly known as declustering, by employing the algorithm of [15]. The earthquake events in the catalogue were further reduced to 7845 as a result of declustering which eliminated about 77% of the events.

Table 1 – Adopted homogenization relations between Mw and other magnitude scales.

Type of magnitude	Homogenization relation	Magnitude Range	R^2	Reference
M_w, m_b	$M_w = 0.967\ m_b + 0.1989$	$4.0 \leq m_b \leq 6.2$	0.7211	Current Study
M_w, M_S	$M_w = 0.5396\ M_S + 2.7051$ $M_w = 0.9336\ M_S + 0.3781$	$3 \leq M_S \leq 6.1$ $6.2 \leq M_S \leq 8.2$	0.73	Current Study
M_w, M_L	$M_L = M_w$	$M_L \leq 6$	-	[16]
M_w, M_D	$M_w = 0.764\ M_D + 1.379$	$3.7 \leq M_D \leq 6.0$	-	[17]

To measure the completeness of the earthquake catalogue there are several methods available. In this study the completeness was analyzed by using two different techniques; Visual Cumulative Method (CUVI) [18] and Stepp [19] method. The results from both methods yielded almost similar completeness ranges as shown in the Table 2.

Table 2 – Periods of completeness for the developed earthquake catalogue.

Magnitude class	Completeness period
$M_w \geq 4.0$	1990 – 2018 = 28
$M_w \geq 4.5$	1975 – 2018 = 43
$M_w \geq 5.0$	1951 – 2018 = 67
$M_w \geq 5.5$	1926 – 2018 = 92
$M_w \geq 6.0$	1900 – 2018 = 118
$M_w \geq 6.5$	1900 – 2018 = 118
$M_w \geq 7.0$	1900 – 2018 = 118
$M_w \geq 7.5$	1884 – 2018 = 134

$M_w \geq 8.0$	1878 – 2018 = 140

3 Modeling of Seismic Source

The characterization of seismic sources consists of two different and independent modeling approaches; (1) The conventional area source model and (2) the active faults and background gridded seismicity model with subduction zone, are adopted to account for the epistemic uncertainty in the modeling. Both source models are organized in a logic tree with 50% probability weights assigned to each model (Fig. 3).

3.1 Area source model

Area sources are generally used to model the background seismicity of the region with mapped or unmapped faults. In this approach, the seismicity of the region is assumed to be uniform and homogeneous. The area sources show the historical seismicity pattern in that region. In this study, Pakistan and the surrounding areas are divided into 23 shallow crustal source zones (0-50 km) and 5 deep source zones (50-250 km), as shown in the Fig.1. The delineation of area sources is performed by considering the seismicity pattern and active crustal faults of the region.

In this study the magnitude frequency distribution (MFD) in the seismic area source zones is characterized by using the truncated Gutenberg-Richter (G-R) law. The maximum likelihood method proposed by Aki (1965) with the modifications of standard deviation error δb [20] is used for the estimation of b value. The seismicity parameters are estimated using the declustered catalogue within the completeness ranges as shown in the Table 3.

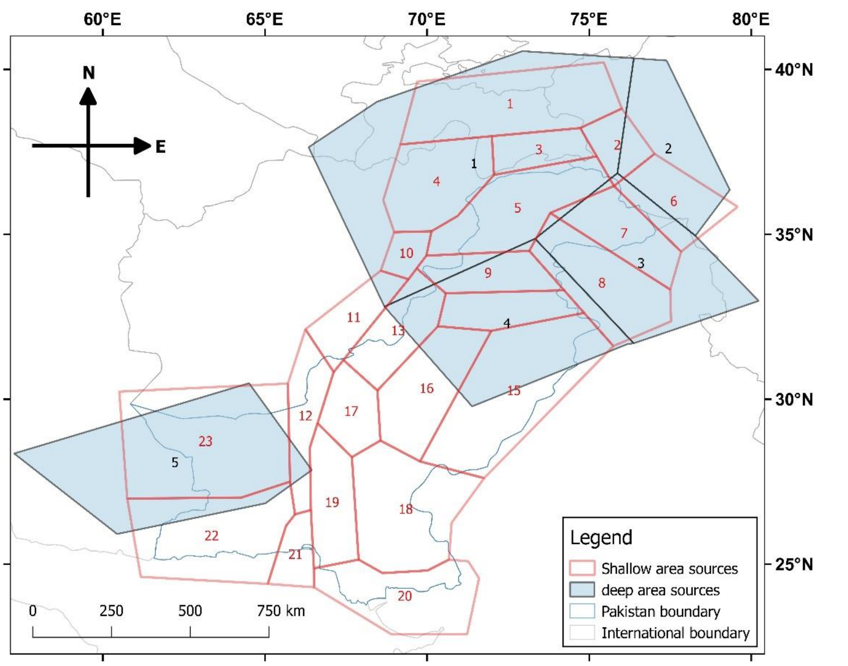


Fig. 1 – Twenty-three Shallow and five deep area seismic source zones, delineated based on historical seismicity and faults.

Table 3 – Seismicity parameters for 23 shallow and 5 deep area sources.

Seismic Zones	Events	a	b	D_{min}	D_{max}	M_{min}	M_{max}
1	637	2.92	0.53	0	50	4	7.6
2	52	3.59	0.874	0	37	4	6.2
3	83	4.87	1.02	0	43	4	6.3
4	239	2.46	0.53	0	50	4	7.5
5	246	2.85	0.60	0	50	4	7.4
6	121	2.72	0.64	0	49	4	7
7	107	6.04	1.23	0	50	4	6.7
8	264	3.63	0.765	0	50	4	7.9
9	136	2.84	0.65	0	48.4	4	7.5
10	57	3.34	0.79	0	50	4	6.8
11	59	2.99	0.74	0	43	4.1	6.2
12	101	3.33	0.741	0	50	4.1	7.6
13	89	3.49	0.82	0	47.2	4	6.1
14	104	2.87	0.63	0	50	4	6.6
15	142	3.73	0.81	0	50	4	7
16	257	3.67	0.76	0	50	4	6.8
17	150	3.69	0.79	0	43	4	7.4
18	70	3.85	0.88	0	50	4	6
19	131	3.18	0.71	0	38.5	4	6.3
20	74	2.42	0.62	0	48	4	7.8
21	23	2.81	0.77	0	44.8	4.2	5.9
22	74	3.13	0.65	0	48	4	7.8
23	133	3.27	0.72	0	50	4	7
Deep Seismic Zones							
1	795	3.5	0.63	50.3	456	4	7.9
2	71	2.45	0.655	50.7	311	4	8.5
3	64	4.69	1.05	50.6	750.6	4	6.7
4	41	2.71	0.664	53	372	4	6.3
5	38	5.42	0.931	50.2	185.9	4.1	7.5

The seismicity parameters are calculated using the aforementioned GR model by employing the ZMAP [21] software package. In shallow seismic sources, the variation of 'b' value is from 0.529 to 1.23, while in deep seismic sources, the values of 'b' varies from 0.63 to 1.05. The seismic activity is higher for the seismic sources located in the Northern part of the country near the Hindukush region. Spatially smoothed seismicity with crustal faults model

3.1.1 Background Seismicity

The background smoothed seismicity model represents the earthquake occurrence pattern of the region in the areas of unmapped faults and smaller magnitude earthquakes in the range of 4 to 6.5 M_W in the buffer zone of 15km on both sides of the crustal faults. The background seismicity is divided into two groups; (1) the unmapped fault zone and (2) the buffer zone around the active crustal faults. In addition to this, the seismicity in each zone is divided into four layers on the basis of their seismogenic depths, ranging from 0-25 km, 25-50 km, 50-100 km and 100 - 250 km. To avoid the duplication of earthquakes linked to the active crustal faults, the earthquake events in the buffer zone having $M_W < 6.5$ are assigned to the background seismicity. Whereas events having $M_W >= 6.5$ are assumed to be faults specific [12]. The Frankel (1995) spatially smoothing algorithm is employed to get the seismicity rates (10^a) at each point in a grid of spacing 0.1° x 0.1° in the study region. For background seismicity (unmapped fault zone), maximum magnitude of M_W 7.4 is assigned, as this is the maximum magnitude observed. Whereas in the buffer zone M_W 6.5 is assigned as M_{max}.

3.1.2 Crustal faults model

The crustal faults information for Pakistan and surrounding areas are primarily obtained from the updated global active faults database of Global Earthquake Model [22] and from the data reported by Kazmi and Jan [23]. A total of 110 active crustal faults in the administrative boundary of Pakistan and the nearby areas within 300km are incorporated and explicitly modeled (Fig.2). The earthquake recurrence rate, for higher magnitude earthquakes on crustal faults is determined from geometric parameters, faulting mechanism and geological slip rate using the seismic moment. There are a number of recurrence models e.g. [24-27] available to estimate the fault seismic activity from geologic slip rates.

For the current study, the Youngs and Coppersmith [25] exponential and characteristic magnitude-frequency distribution models are used with equal probabilistic weight of 50% assigned to each. The important inputs in the recurrence models are slip rate and value of 'b'. The regional b value of 0.9, estimated from the seismicity of the whole country, and is kept constant for all faults. The Wells and Coppersmith [28] empirical relationship is used for characterizing the maximum magnitude of faults using geometry.

To deal with the double-counting of the seismicity from background and active faults, a threshold magnitude of M_w 6.5 (used by ESHM13 and Petersen, Frankel [12]) is selected to separate the earthquakes associated to the background from that of the active faults. A symmetric buffer zone (15km) is created on both sides of the active crustal faults. Events having magnitudes smaller than M_w 6.5 are assumed to have occurred in the background buffer zone, whereas events larger than M_w 6.5 are assumed to be fault specific.

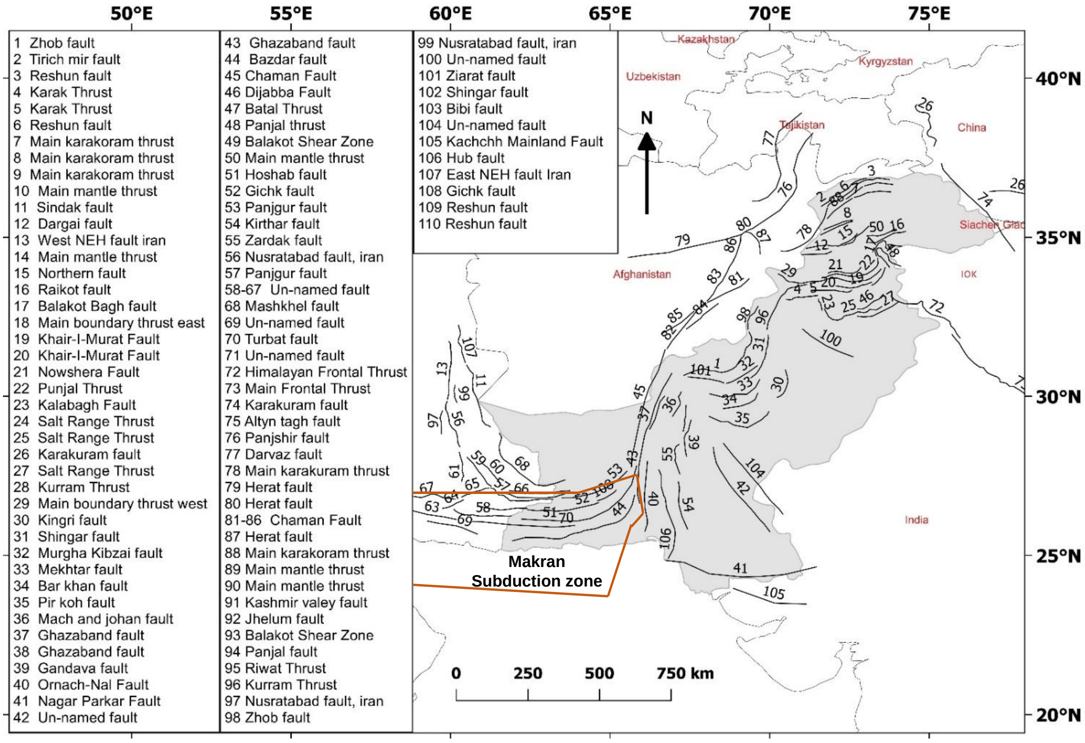


Fig. 2– Active crustal faults of Pakistan obtained from the GEM (2019) active crustal faults database and Kazmi and Jan [23]

3.1.3 Makran Subduction Zone Model

The Arabian plate is subducting under the Eurasian plate with a dip angle of 10 degrees extending 400-500 km towards the north [29]. The annual subduction rate of the Makran Subduction Zone (MSZ) is between 32 to 35 mm/year [30] on the eastern side. While at the western side between Oman and Iran the convergence rate is 19.5 mm/years [31].

To model the Makran subduction zone, the earthquake events in the subduction zone are divided into very shallow (0-5km), shallow (5-55km), intermediate (55-100km) and deep (100-250km). The activity of the Makran Subduction Zone is modeled using three types of seismogenic source models. (1) The faults and folds appearing on the upper surface of the subduction zone, (2) The shallow seismicity (5-55km) is modeled as complex inclined area source zone and (3) the very shallow, intermediate and deep earthquakes are modeled as spatially smoothed seismicity similar to the background seismicity. To characterize the seismicity of the complex area source, the Gutenberg-Richter magnitude recurrence model is used, with M_W 8.2 as maximum magnitude M_{max}

4 Ground Motion Prediction Equations (GMPEs)

To deal with the epistemic uncertainties in the ground motion models, multiple ground motion models are selected for each seismogenic source in a logic tree (**Error! Reference source not found.**). The Next Generation Attenuations models (NGA west 2) [32] are applied to very shallow (0 – 25km), shallow (25 - 50km) and crustal faults in the area. The GMPEs consists of Campbell and Bozorgnia [33], Atkinson and Boore [34] and Chiou and Youngs [35]. An equal weightage of 0.333 is assigned to each of the above GMPEs.

To estimate the ground motion for earthquakes in the intermediate (50-100 km) and deep (100-250 km) layers, GMPEs by Youngs, Chiou [36] and Atkinson and Boore [37] are selected. Youngs, Chiou [36] is used for earthquakes having depth ranging from 50km to 250km, whereas Atkinson and Boore [37] is used only for intermediate (50-100 km) seismicity as shown in the logic tree (Fig.3). For the Makran Subduction Zone, the ground motion for subduction interface is calculated using three GMPEs developed by Atkinson and Boore [37], Youngs, Chiou [36] and Zhao, Zhang [38] with probability weight of 0.333 for each. The GMPEs used in this study are the latest understanding of ground motions in their regions [12].

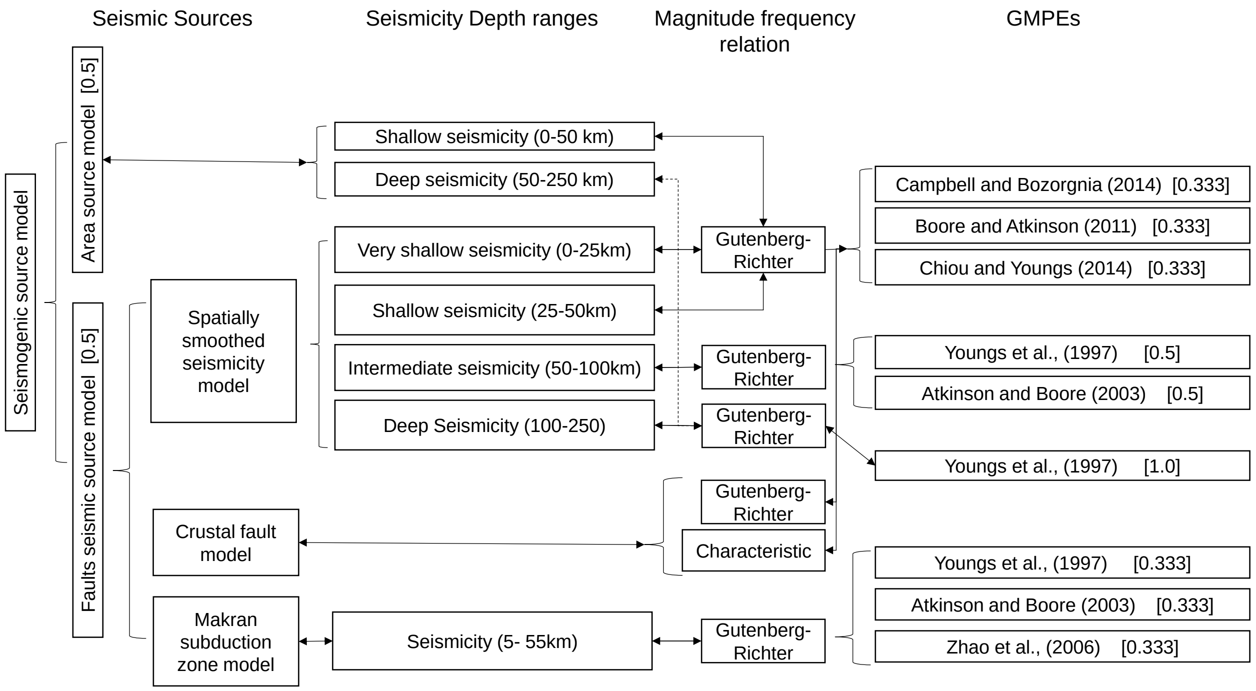


Fig. 3 – The main logic tree used for the seismic source model and GMPEs for performing the PSHA. Values in the bracket show the weights for GMPEs.

5 Probabilistic seismic hazard assessment and results

In this study, the PSHA for Pakistan is carried out using state of the art OpenQuake engine [39]. The whole study area is divided by a grid of 0.1° x 0.1° (approximately 11 km) in both directions that resulted about 54,333 sites. The hazard maps (Fig.4) for the mean PGA and SA (0.2s, 1s and 2s time periods) have been developed for 10% and 2% Probability of Exceedance (PE), corresponding to 475 and 2475 years return period, with 5% critical damping ratio. The logic tree approach is used to incorporate the uncertainties of two source models and various GMPEs for each tectonic region. The hazard maps are developed for the standard reference site condition, proposed by NEHRP (National Earthquake Hazard Reduction Program) site class B and C, with average shear wave velocity of 760 m/s in the top 30 m of the crust. A wide range of variation in the hazard values, ranging from 0.1 to 0.7g for 10% PE and 0.15 to 1.2g for 2% PE is estimated within Pakistan. The PGA values for 2475 years return period are 1.54 to 2.8 times greater than PGA values for 475 years return period.

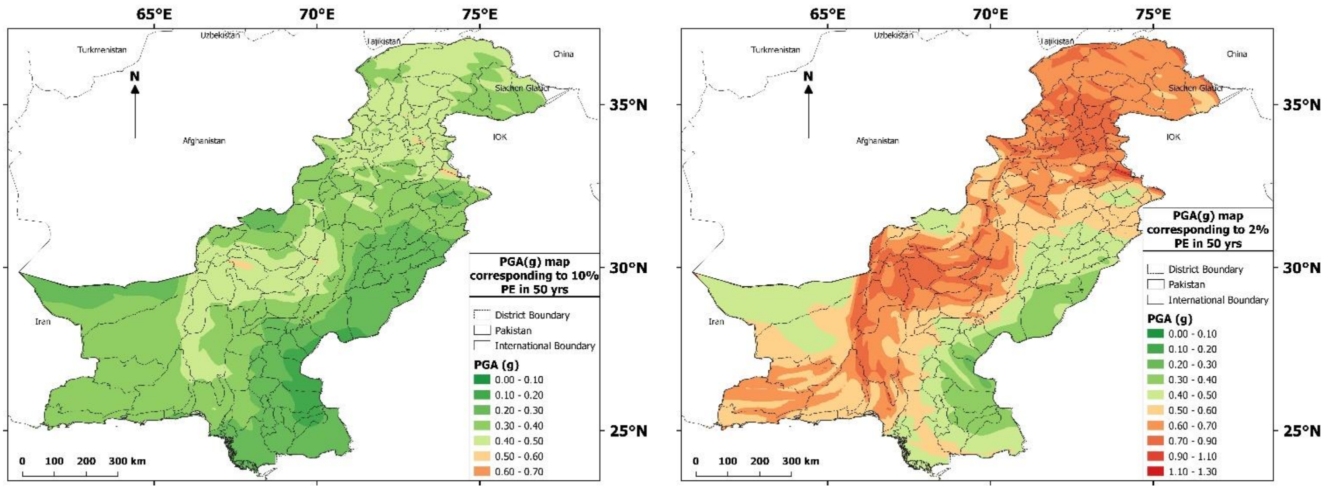
Generally, the hazard values are higher in the northern areas of Pakistan (Chitral, Gilgit, Swat, Dir, Kohistan, Mansehra and Abbotabad) and Azad Jammu and Kashmir (Mirpur, Muzaffarabad, Neelam and Bagh), due to higher seismicity in the Hindukush, Pamir and Karakorum ranges. In the western areas of Pakistan (Quetta, Ziarat, Mastung, Chaman and Sibi), higher hazard values are obtained due to the strike slipping faults (Chaman fault and Ghazaband fault). In the southwestern Pakistan (Gawadar, Kharan and Panjgur), the higher hazard values are estimated due to the Makran Subduction Zone. The eastern Pakistan (i.e. southern

Punjab) is identified as at comparatively lower hazard. The Himalayan Frontal Thrust, Main Boundary Thrust, Jehlum fault and Riwat fault have the potential of producing larger earthquakes that may affect larger cities, such as Islamabad, Rawalpindi and areas of Azad Kashmir.

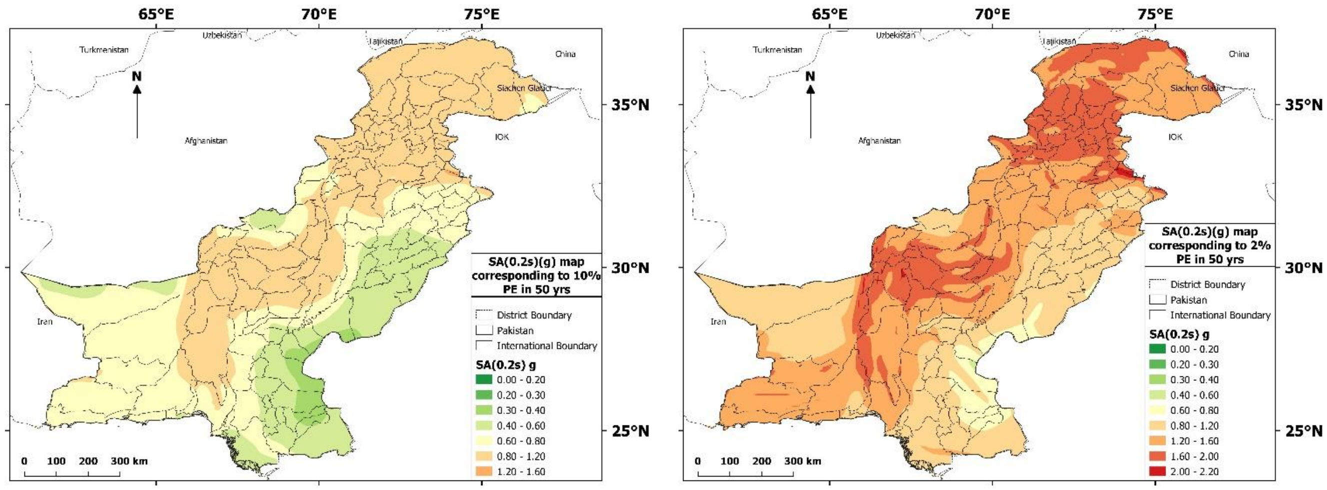
6 Conclusions

This paper briefly describes the methodology used to develop the seismic hazard maps of Pakistan. In this study the latest approaches developed for the National Seismic Hazard Map (NSHMP) of US and the Earthquake Model for Middle East (EMME) are used. This study will serve as a reference for further updating the local and national level seismic hazard maps. Two different approaches (the conventional area source and spatially smoothed seismicity with active faults) are employed to assess the seismic hazard using an up-to-date recompiled earthquake catalogue. To cater the epistemic uncertainties in the models, the logic tree procedure is adopted. Hazard maps are developed for PGA and SA at various time periods, for 10% and 2% probability of exceedance in 50 years. The PGA value within Pakistan varies from 0.05 to 0.18 g, 0.1 to 0.7 g and 0.15-1.20 g corresponding to return periods (RP) of 475 and 2475 years. The hazard values are mostly higher near the plate boundary, major active faults and subduction zone. The hazard maps show a little higher values, however similar pattern to that of the previous studies [2, 7, 10, 13, 40]. By using the latest paleoseismic active fault data, latest earthquake catalogue and improved GMPEs, the hazard maps developed for Pakistan are considered to be relatively more improved as compared to the previous studies. The updated PSHA of Pakistan has improved the understanding of seismic hazard of Pakistan. The hazard maps will have a positive impact on the seismic risk mitigation of Pakistan by improving the construction practice throughout the country, which is one of the most seismically active and vulnerable areas of the region.

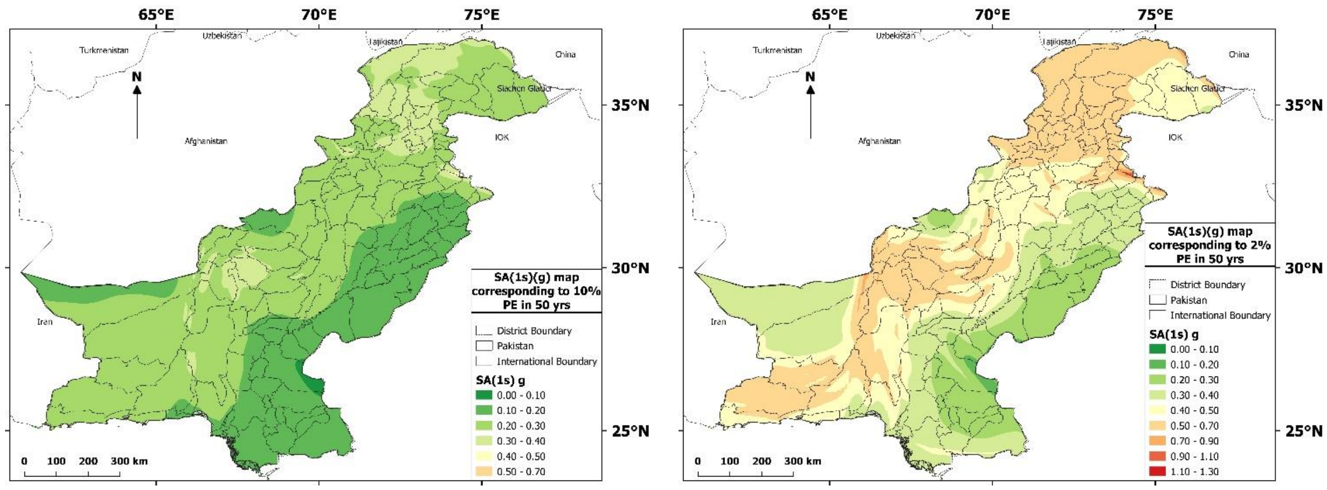
(a)



(b)


SA(0.2s)(g) map corresponding to 10% PE in 50 yrs
District Boundary
Pakistan
International Boundary
SA(0.2s) g
0.00 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.60
0.60 - 0.80
0.80 - 1.20
1.20 - 1.60
SA(0.2s)(g) map corresponding to 2% PE in 50 yrs
District Boundary
Pakistan
International Boundary
SA(0.2s) g
0.00 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.60
0.60 - 0.80
0.80 - 1.20
1.20 - 1.60
1.60 - 2.00
2.00 - 2.20
65°E
70°E
75°E
35°N
30°N
25°N
Turkmenistan
Uzbekistan
Tajikistan
China
Siachen Glacier
IOK
Afghanistan
Iran
N
0 100 200 300 km

(c)


SA(1s)(g) map corresponding to 10% PE in 50 yrs
District Boundary
Pakistan
International Boundary
SA(1s) g
0.00 - 0.10
0.10 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.50
0.50 - 0.70
SA(1s)(g) map corresponding to 2% PE in 50 yrs
District Boundary
Pakistan
International Boundary
SA(1s) g
0.00 - 0.10
0.10 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.50
0.50 - 0.70
0.70 - 0.90
0.90 - 1.10
1.10 - 1.30
65°E
70°E
75°E
35°N
30°N
25°N
Turkmenistan
Uzbekistan
Tajikistan
China
Siachen Glacier
IOK
Afghanistan
Iran
N
0 100 200 300 km

(d)

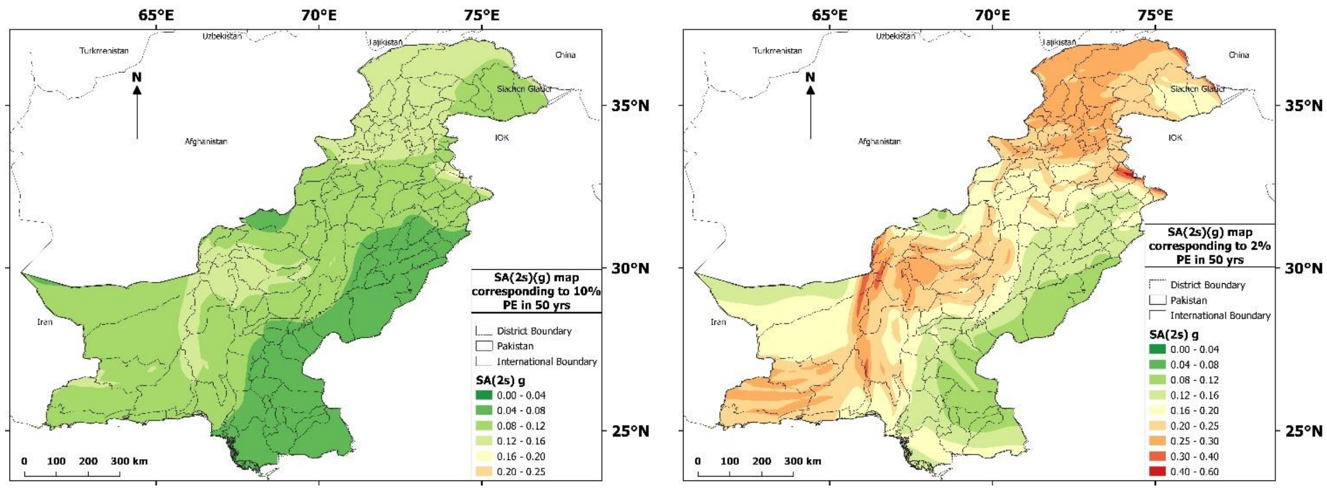

SA(2s)(g) map corresponding to 10% PE in 50 yrs
District Boundary
Pakistan
International Boundary
SA(2s) g
0.00 - 0.04
0.04 - 0.08
0.08 - 0.12
0.12 - 0.16
0.16 - 0.20
0.20 - 0.25
SA(2s)(g) map corresponding to 2% PE in 50 yrs
District Boundary
Pakistan
International Boundary
SA(2s) g
0.00 - 0.04
0.04 - 0.08
0.08 - 0.12
0.12 - 0.16
0.16 - 0.20
0.20 - 0.25
0.25 - 0.30
0.30 - 0.40
0.40 - 0.60
65°E
70°E
75°E
35°N
30°N
25°N
Turkmenistan
Uzbekistan
Tajikistan
China
Siachen Glacier
IOK
Afghanistan
Iran
N
0 100 200 300 km

Fig. 4 – Pakistan hazard map for (a) PGA, (b) SA(0.2s), (c) SA(1s) and (d) SA(2s) corresponding to 10% (475 years RP) and 2% (2475 years RP) probability of exceedance in 50 years.

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