Probabilistic Seismic Hazard Maps for Pakistan

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SUMMARY:
Probabilistic seismic hazard assessment of Pakistan has been carried out using the latest procedure developed for the US National Seismic Hazard Maps. The present assessment is based on the combination of spatially smoothed gridded seismicity at three depth intervals: shallow (0-50 km), intermediate (51-100 km), and deep (101-250 km), thirteen crustal fault, and subduction source models, with most updated ground motion prediction equations (GMPEs). Existing earthquake catalogues of Pakistan are compiled into a new composite earthquake catalogue, containing instrumental earthquake records from 1902 to 2009 within a region bounded between latitude 20^{o}- 40^{o}N and longitude 58^{o}- 83^{o}E. The final result of this assessment consists of seismic hazard maps for peak ground acceleration for 10% and 2% probabilities of exceedance in 50 years. The main findings are that the hazard dominates in northwest, western Pakistan is controlled by both faults and seismicity and southwestern Pakistan is controlled by the Makran subduction zone

Keywords: *Seismic Hazard Map, Pakistan.*

1. INTRODUCTION

Pakistan locates in the tectonically active Himalayan orogenic belt that developed by the collision among the Indian, Arabian, and Eurasian plates over the last 30-40 million years (Ma), (Aitchinson et al., 2007). Moderate to large earthquake magnitudes are common in this region and will continue to occur as long as the tectonic deformation continues. Some of these earthquakes caused serious damage to buildings and infrastructures through strong ground shaking and also, in some cases, faults rupturing the ground surface. A vivid example is the devastating October 8, 2005, M_w7.6 Kashmir earthquake in northern Pakistan. The destructive and deadly hazards associated with earthquakes pose a real and serious threat to the life of people, property damage, economic growth and development of the country. A proper understanding of the distribution and level of seismic hazard throughout the country is therefore necessary.

All existing seismic hazard maps of Pakistan developed by several investigators (e.g., National engineering services of Pakistan (NESPAK, 2007); Pakistan meteorological department seismic hazard map (PMD, 2007); and Global seismic hazard assessment program, (GSHAP, 1999); have been made following the classical Cornell (1968) and McGuire (1978) approach. In these studies, seismic sources are modelled as area source zones where each zone is assumed to have a uniform rate of seismicity. These hazard maps are, however, appeared to be influenced by the delineation of seismic source zones, which could be heavily dependent on the subjective judgment of the hazard analyst. To overcome this problem, new probabilistic seismic hazard maps for Pakistan are developed by applying the Frankel (1995)'s spatially-smoothed gridded seismicity approach. In addition, crustal faults and a subduction zone known as Makran are modelled as seismic sources explicitly. For handling the epistemic uncertainty, logic tree frame work is used.

2. PAKISTAN AND ITS REGIONAL TECTONIC SETTING

Pakistan lies on the western edge of the Indian plate, bordered to the west and north by the Eurasian plate and to the southwest by the Arabian plate as shown in Fig. 1. All these three plates are mutually converging, although the mechanisms differ from northern part to southwestern zone. Figure 1 shows black arrows with marks 1, 2, and 3. Mark-1 arrow indicates the Himalayas collision zone in the north. In this area, there is a typically head-on collision from south to north, translating into dip-slip faults (see more details in Fig. 2). Mark-2 arrow shows the west collision. This collision is oblique-slip transpressional (oblique shear), as reflected in the Chaman fault zone and the western thrust-fold belt. Mark-3 arrow points further to the southwest, showing the Eurasia-Arabia convergence which is taking place along the north-dipping active Makran subduction zone (MSZ), (Jacob and Quittmeyer, 1979).

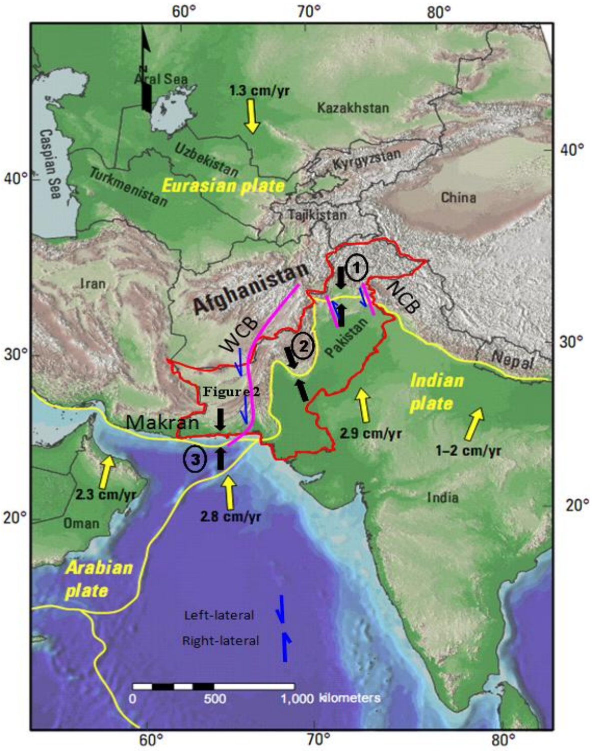

Figure 1. Location of Study Area—Pakistan is bounded by red color line (modified from USGS 2007)

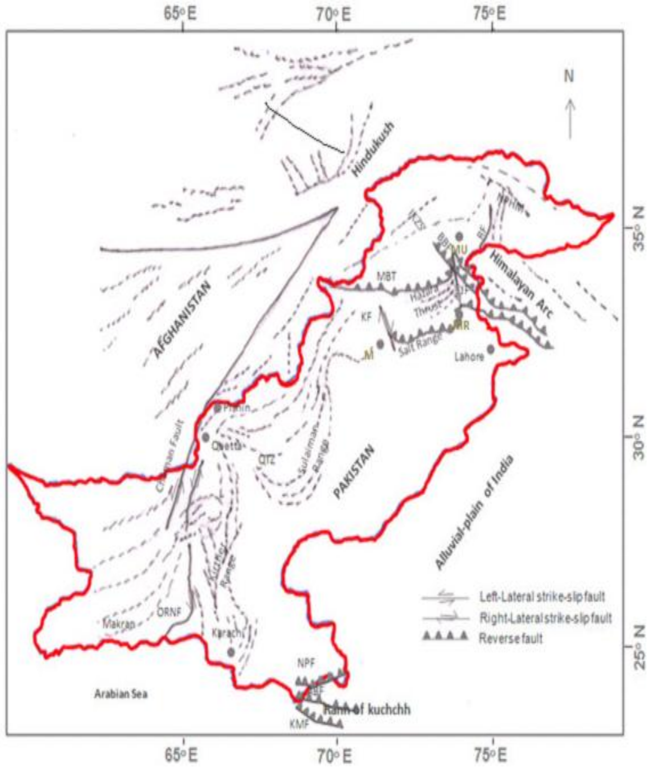

Figure 2. Regional tectonic setting of Pakistan (modified from Sarwar et al., 1979 and PMD, 2007)

3. EARTHQUAKE CATALOGUE

In this study a new earthquake catalogue has been recompiled by combining five pre-existing catalogues for the study area: (1) The USGS/NEIC preliminary determination of epicenters on-line catalogue (PDE) for earthquake records from 1973 to 2009 (http://neic.usgs.gov), (2) International seismological centre (ISC) catalogue from 1905 to 2007 (http://www.isc.ac.uk), (3) catalogue of earthquakes from 1914 to 1975 compiled by Quittmeyer (1979), (4) the global centroid-moment tensor (GCMT project from 1976 to 2008 (http://www.globalcmt.org/CMTsearch.html), and (5) catalogue of earthquakes from 1902 to 2006 compiled by (NESPAK, 2007). By compiling all these catalogues, the resulting earthquake catalogue for Pakistan and neighbouring areas contains instrumental earthquake records from 1902 to 2009 with in a region bounded by latitude 20°- 40°N and longitude 58°-83°E.

A single representative scale of magnitude has to be chosen for each earthquake, as the compiled earthquake catalogue, have several magnitude scales such as: the 20-s surface-wave magnitude (M_s) and the short-period P-wave magnitude (m_b) are commonly used in the data from USGS and ISC, the local magnitude (M_L) is recorded by PMD, and the moment magnitude (M_w) is reported in the GMCT catalogue. In this study, the moment magnitude scale is selected as the representative scale for each earthquake. For magnitude selection our order of preference is M_w, M_s, m_b, and M_L. Magnitudes are converted to moment magnitude using the relations of Scordilis et al., (2006) (M_s and m_b to M_w) and Heaton et al., (1986) (M_L to M_w), After the magnitude conversion, duplicated events (from different data sources) are merged into a single entry for each earthquake event. The catalogue of unduplicated events contains 18,324 earthquake events with $M_w \geq 4.0$.
Our seismic hazard methodology is based on the assumption that the probability of the occurrence of an earthquake in a given period of time follows a Poisson distribution. Thus the earthquake catalogue

used for carrying out seismic hazard assessment must be free of dependent events such as foreshocks and aftershocks. This process is called declustering. We apply the algorithm of Gardner and Knopoff (1974) to decluster the earthquake catalogue. Declustering eliminates about 68% of the events in the earthquake catalogue. The final declustered catalogue contains 5,911 earthquake events with $M_w \geq$ to 4.0 in the study region from 1902 to 2009 (see Fig. 3). After declustering we estimates the completeness level for several prescribed earthquake magnitude ranges by using the Visual Cumulative method (CUVI) (Tinti and Mulargia, 1985). The resulting time periods using CUVI method are: 2000-2009 for $M_w \geq 4.0$, 1995-2009 for $M_w \geq 4.5$, 1977-2009 for $M_w \geq 5.0$, 1964-2009 for $M_w \geq 5.5$, 1960-2009 for $M_w \geq 6.0$, 1920-2009 for $M_w \geq 6.5$, and 1912-2009 for $M_w \geq 7.0$, 1902-2009 for $M_w \geq 7.5$, and 1902-2009 for $M_w \geq 8.0$.

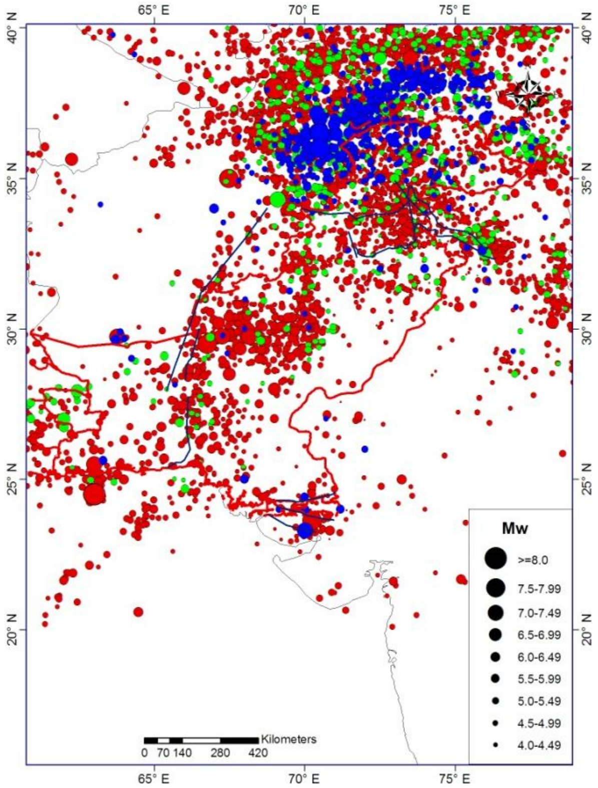

Figure 3. Pakistan and its surrounding seismicity from 1902 to 2009; red: 0-50 km depth, green: 51-100 km depth, and blue: 101-250 km depth

4. MODELLING OF EARTHQUAKE SOURCES

To properly describe the complex earthquake environments in the region, they are modelled as a mixture of background seismicity, crustal faults and subduction zone shown in Fig. 4. They are described in more detail below.

4.1. Background seismicity model

The background seismicity model represents random earthquakes on unmapped faults and smaller earthquakes on mapped faults in the whole study region except the MSZ. The area with unmapped fault is called background unmapped fault seismicity zone (BUFSZ) and the area with mapped fault is called background fault seismicity zone (BFSZ) having a width of about 40 km throughout the length of the fault. The rate of seismicity is assumed to vary from place-to-place within these zones. We separated the earthquake catalogue for both zones. The earthquake catalogue of BUFSZ is subdivided into three depth ranges, 0-50 km, 51-100 km, and 101-250 km (see Fig. 3), while the BFSZ catalogue contain only shallow earthquakes events. The rate of seismicity is determined by first overlaying a grid with a given spacing, in the current case 0.10º in latitude and longitude (about 10 km on side) onto the study region, and counting the number of earthquakes with magnitude greater than a reference value *(M_{ref})* in each grid cell. The rate of seismicity is computed by dividing the number of earthquakes by the time period of complete earthquake data. The rate is then smoothed spatially by a Gaussianfunction moving average and comparing with the observed seismicity. All earthquake data with $M_w \geq$ 4.0 are used for the seismicity rate calculation. The magnitude-dependent characteristic of the seismicity rate is modelled by a truncated exponential model (Gutenberg-Richter model (GR)):

$$Log_{10}(N(M_w)) = a - bM_w \qquad (1)$$

where $N(M_w)$ is the annual occurrence rate of earthquakes with magnitude greater than or equal to M_w, and a and b are the GR model parameters. The b parameter is assumed to be uniform in both background (BG) zones. The computed b-value from the complete earthquake data with $M_w \geq 4.0$ is 0.95. For both BG zones earthquake data with $M_w \geq 4.0$ are used.

The a-value for all three depths subset in BUFSZ and shallow depth earthquake in BFSZ has been spatially smoothed using a two-dimensional Gaussian moving operator with a correlation distance parameter C = 50 km (Frankel 1995), the computed smoothed rate 10^a values for three spatially smoothed-seismicity subsets in BUFSZ are presented in Fig. 5 is in agreement to observed spatial pattern of seismicity. In order to avoiding double-count earthquakes in the truncated GR model of BFSZ the minimum earthquake magnitude (M_{min}) is set to 4.5 and the maximum magnitude (M_{max}) is set to 6.5, While for BUFSZ, the M_{min} is set to 4.5 and M_{max} is set to 7.4. Larger earthquakes will be accounted for by crustal fault models.

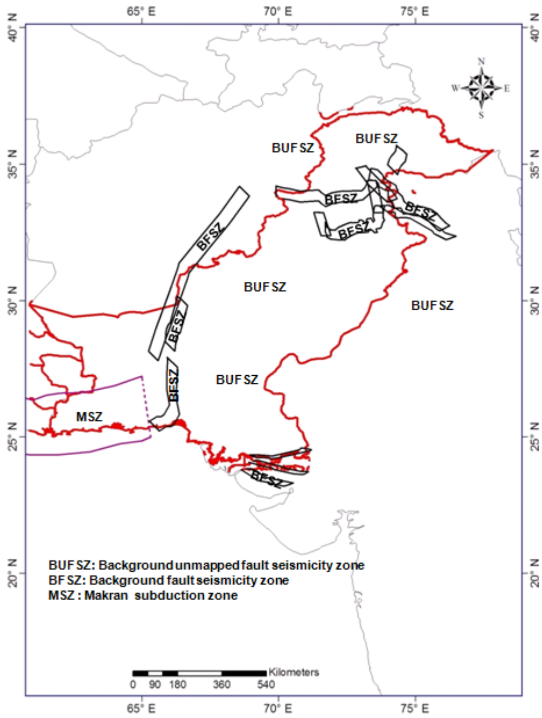

Figure 4. Earthquake sources of the study area: Background unmapped fault seismicity zone (BUFSZ), Background fault seismicity zone (BFSZ), and Makran subduction zone (MSZ)

4.2 Makran subduction zone model

The boundary of MSZ is taken from Jacob and Quittmeyer (1979), Byrne et al., (1992), and Heuret et al., (2011) shown in Fig. 4. The boundary of MSZ shown in figure 4 is modelled as a traditional area source model (assuming uniform rate of seismicity) and to model the earthquake-recurrence behaviour, truncated GR relation is employed. The GR model parameters (a and b values) calculated for MSZ are 3.372 and 0.716. The M_{min} in the GR model is set to 6.5 and the M_{max} for MSZ is set to 8.7, which is equal to the maximum observed magnitude plus 0.5 magnitude units. A subduction earthquake is assumed to be created by rupture along an inclined plane at the interface between two tectonic plates. The fault plane ranges from 5 km depth at the deformation front down to 35 km depth at the southern boundary.

4.3 Crustal fault source model

The information about crustal faults in and near Pakistan is mainly obtained from various past studies. These studies comprises of investigation which were carried out using geomorphic expression of faulting (aerial photographic interpretation), Recurrence interval (RI) of large earthquakes, and field investigation (trenching). Thirteen faults in Pakistan are considered in this study; they are listed together with their important properties in Table 1. They can be classified into two main types: strike slip and reverse faults (see Fig. 6). In the following, more details about the faults are presented since they are likely to contribute significantly to the seismic hazard assessment.

(1). Kalabagh fault (KF): Kalabagh fault is a prominent right-lateral strike slip fault, located on the east of Kalabagh, and extending between Kalabagh and Mianwali (M). Overall trend of the fault is northwest-southeast. It truncates the western margin of Salt Range. Slip rates for the Kalabagh fault is about 7.6-10 mm/yr, with 16-19 km of offset in the last 1.9-2.1 Ma (McDougall et al., 1990). Maximum weight has been assigned to low slip rate as the RI of faulting is long probably in thousands of years (Yeats et al., 1984).

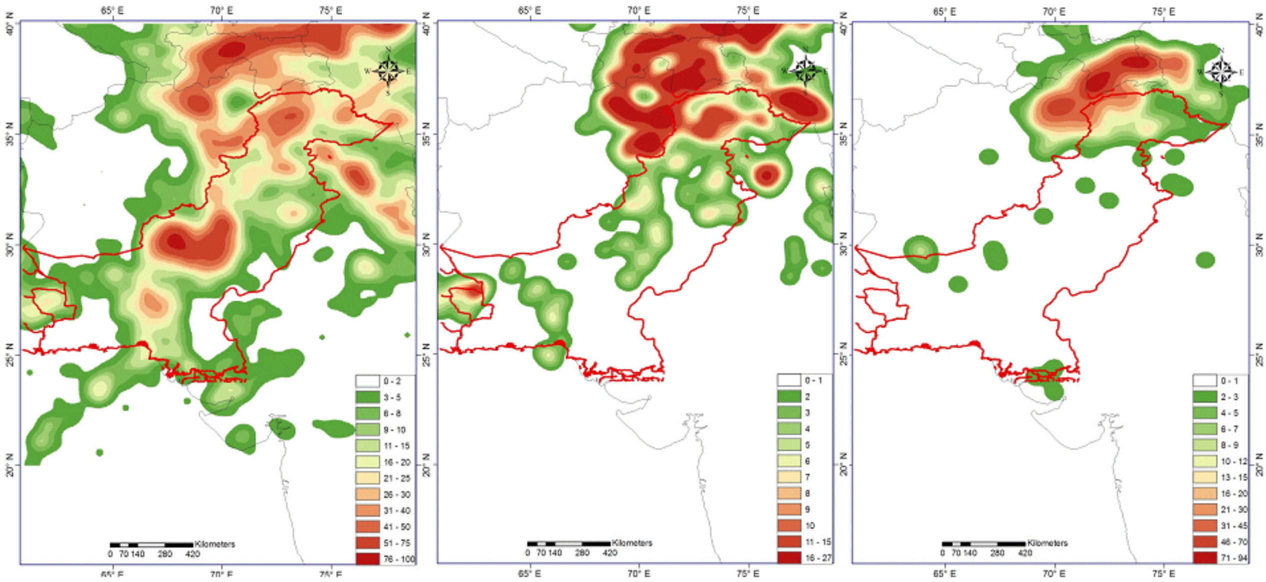

Figure 5. Smoothed activity rate 10^a value derived for seismicity from 0-50km, 51-100 km and 101- 250 km depth

(2). Salt Range thrust (SRT): The SRT defines the frontal thrust in Pakistan and marks the southern margin of the Hazara arc. According to Baker (1988) SRT absorbing at least 9-14 mm/yr of north-south shortening.

(3). Main Boundary Thrust (MBT): The Sub-Himalaya is bounded on the north by MBT. MBT is mostly inactive, although it is known to locally displace late Quaternary surfaces and deposits in the Indian and Nepali Himalaya. Meigs et al., (1995) estimates displacement rate of 10 mm/yr for MBT based on the present seismicity and displacement on the thrust.

(4). Jhelum fault (JF): Jhelum fault is north-south trending fault, follows the Jhelum river from Muzaffarabad (MU) to Murree (MR). During the seismic study for the New Bong Escape Hydropower Project in Pakistan in 2005 for the design of the powerhouse, they adopted an earthquake of RI of 1000 years on Jhelum fault.

(5). Himalayan Frontal Thrust (HFT): HFT marks the southern margin of the Himalayan range is the source of some major earthquakes for the past 200 years. Wenousky et al., (1999) estimates the slip rate of about 13.8±3.6 mm/yr based on the displacement of stream level and radiocarbon ages of deposit terraces. According to Seeber et al., (1981) both SRT and HFT in Pakistan, are overlain by salt and having no capability of producing large earthquake, therefore maximum weight has been assigned to low slip rate.

(6). Balakot-Bagh (BB) fault: The northwest-striking BB fault is the source of 2005 Kashmir earthquake of M_w7.6. The fault follows the Indus-Kohistan Seismic Zone (IKSZ). Kondo et al., 2008 estimate the slip rate of 3 mm/yr for BBF using data from trenching study.

(7). Raikot fault: Nanga Parbat-Haramosh Massif (NPHM) is the tallest mountain in Pakistan and seismically active area. In Nov, 2002 it was affected by two devastating earthquakes of m_b 5.3 and 6.2. Field evidences show that along the western side of Nanga Parbat-Haramosh massif there is an active fault present known as Raikot fault. The slip rate of Raikot Fault is about 5 mm/yr (Shroder et al., 1989).

(8). Chaman fault system: The Chaman fault system is about 850 km long, extending from Afghanistan into western Pakistan. Based on studies of aerial photographs and Quaternary geomorphology, Wellman (1965) estimated slip rates on the Chaman fault system between 2 and 20 mm/yr. Maximum weight has been assigned to mean slip rate, as the mean slip rate value of chaman fault is approximately equal to the value that was used in past study (Boyd et al., 2007).

(9). Ghazaband fault: Ghazaband fault lies in the east of Chaman fault in axial belt within 80 km, exhibit a left-lateral displacement with smaller slip rate of about 1 mm/yr.

(10). Ornach-Nal fault: Ornach-Nal is southernmost strike-slip fault collectively termed the Chaman fault system (Yeats et al., 1979) define the western edge of the Indian plate. Lawrence et al., (1992) estimated its slip rate from geological offsets which is about 20-40 mm/yr. As Ornach-Nal fault is southward continuation of Chaman fault so we also give maximum weight to mean slip rate.

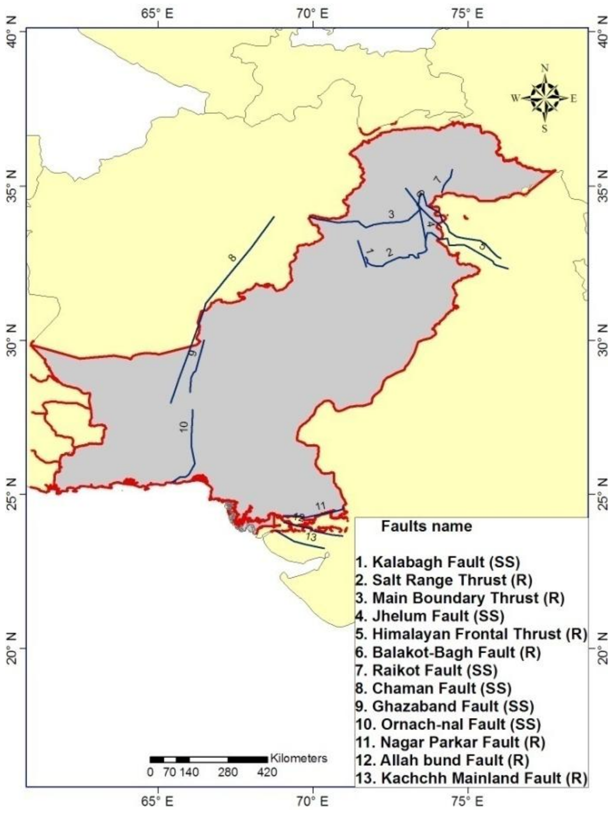

Figure 6. Thirteen crustal fault source models incorporating in this study (SS: Strike-Slip fault, R: Reverse fault)

(11-13). Rann of Kuchuhh faults: Rann of Kuchuhh is the east-west oriented high lands (uplifts) and low lying basins. A number of east-west faults control the structural trend of the Kutch rift, are Nagar Parkar fault (NPF), Allah Bund fault (ABF), and Kachchh Mainland fault (KMF). (See Fig. 2). Rajendran and Rajendran (2002) suggest that the ages of liquefaction features near the Allah Bund fault imply 800 to 1000 years RI for earthquakes similar to the 1819 earthquake. Slip rate has been estimated using this RI for a Rann of Kuchuhh faults. We give similar weight to all values of slip rate as they are estimated from RI of 800 to 1000 years.

The fault rupture length is estimated from the characteristic earthquake magnitude by using the Well and Coppersmith (1994) formula. Each strike-slip fault is assumed to rupture along a vertical plane, while each reverse fault is assumed to rupture along an inclined plane with a dip angle of 60°. The fault width is determined by assuming a seismogenic depth of about 25 km and then using the dip, so that the width equaled 25 km divided by the sine of the dip. Two different types of approaches are employed to model the earthquake-recurrence behaviour, i.e. GR model and characteristic earthquake (CE) model. To account for the uncertainty in estimating M_{max}, we consider three different cases with M_{max} set to M_C *- 0.2*, M_C, and M_C *+ 0.2*. The probabilistic weights of 0.2, 0.6, and 0.2 are assigned to these cases, respectively. In each case, the *b*-value is set equal to the regional *b*-value of 0.95, and *a*-value is determined from the seismic moment rate, which is computed from the fault slip rate.

In CE model, three characteristic earthquake magnitudes are also considered: M_C *- 0.2*, M_C, and M_C *+ 0.2*. The probabilistic weights of 0.2, 0.6, and 0.2 are assigned to these cases, respectively. The magnitude is assumed to be normally distributed around the characteristic value with a standard deviation of 0.12. The RI for the characteristic model is determined from:

$$RI = \mu \dot{u} LW / M_{oC} \quad (2)$$

where μ is shear modulus, 3.0×10^{11} dyne/cm^2, $\dot{u}$ is the fault slip rate, L is rupture length, W is rupture width, and M_{oC} is the characteristic earthquake moment. We apply 50 percent probabilistic weight in the logic tree for CE and GR magnitude frequency distributions.

Table 1. Crustal fault source model parameter

No.	Fault Name	Fault Type	Length (Km)	Width (Km)	Dip angle	Mag	Slip rate (mm/yr)			Logic tree weight			Recurrence interval (years)		
							Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
1	Kalabagh Fault	SS	120	25	90°	7.5	7.6[a]	8.8	10	0.5	0.4	0.1	292	252	222
2	Salt Range Thrust	R	100	28	60°	7.4	9.0[b]	11.5	14	0.5	0.4	0.1	187	146	120
3	Main Boundary Thrust	R	197	28	60°	7.8	-	10[c]	-	-	1.0	-	-	340	-
4	Jhelum Fault	SS	120	28	90°	7.5	-	0.222[d]	-	-	1.0	-	-	1000	-
5	Himalayan Frontal Thrust	R	297	25	60°	7.8	10.0[e]	13.8	17.4	0.7	0.2	0.1	221	164	130
6	Balakot–Bagh fault	R	135	28	60°	7.6	-	3.0[f]	-	-	1.0	-	-	829	-
7	Raikot Fault	SS	44	25	90°	7.0	-	5.0[g]	.	-	1.0	-	-	215	-
8	Chaman Fault	SS	425	25	90°	7.9	2[i]	11	20	0.1	0.8	0.1	1246	227	125
9	Ghazaband fault	SS	150	25	90°	7.6	-	1[h]	-	-	1.0	-	-	2505	
10	Ornach-Nal Fault	SS	150	25	90°	7.6	2[i]	11	20	0.1	0.8	0.1	1252	228	125
11	Nagar Parkar Fault	R	44	28	60°	7.0	0.61	0.81[d]	1.21	0.3	0.3	0.3	1574	1186	794
12	Allah Bund Fault	R	112	28	60°	7.8	1.33	1.77_d	2.65	0.3	0.3	0.3	1603	1201	801
13	Kachchh Mainland Fault	R	164	28	60°	7.7	1.81	2.42[d]	3.63	0.3	0.3	0.3	1597	1195	796

a = McDougall et al., 1990 (offsets of the topography for the last 2 million year) b = Baker et al., 1988 Stratigraphic evidence, paleomagnetic dating, sediment-accumulation), c = Meigs et al., 1995, d = Recurrence interval, e = Wesnousky et al., 1999 (Offset Holocene terraces), f = Kondo et al., 2008 (Trenching study), g = Shroder et al., 1989, h = Nakata et al., 1990 (offsets of the topography for the last Pluvial (15,000-11,000 yrs B.P.), i = Wellman (1965) and Tapponier et al., 1981 (Based on studies of Aerial Photographs and Quaternary Geomorphology), (SS = Strike-Slip and R = Reverse)

5. GROUND MOTION PREDICTION EQUATIONS (GMPEs)

In this study we apply different sets of GMPEs for shallow crustal earthquakes, subduction zone earthquakes on the plate interface, as well as intermediate and deep in slab earthquakes as the excitation of seismic energy and wave-propagation effects are different for earthquakes in different depth ranges**.**

Shallow crustal earthquakes: Three Next Generation Attenuation (NGA) models developed for shallow crustal earthquakes in the Western United States are applied for the first time to this region to estimate ground motions for shallow background earthquakes in BG and for earthquakes from crustal faults. These NGA models are developed by Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008) during the NGA project. Equal logic tree weights have been assigned to each of these three models.

Intermediate and deep earthquake: To calculate ground motions for intermediate-depth earthquakes (51-250 km), we use the GMPE developed by Atkinson and Boore (2003) for earthquakes from 50 to 100 km depth (intraslab) and a relation developed by Youngs et al., (1997) for earthquakes from 50 to

250 km depth (intraslab, rock site condition). Logic tree weights of 0.50 are used for each model between 50 and 100 km depth in the logic trees analysis.

Subduction zone earthquake: For subduction-zone interface earthquakes we adopt the subduction zone ground-motion models developed by Youngs et al., (1997), Atkinson and Boore (2003; 2008) (both of which are based on global data), and Zhao et al., (2006) (mainly based on Japanese data). Logic tree weights assigned to these models are 0.25, 0.25, and 0.50, respectively.

6. PROBABILISTIC SEISMIC HAZARD ANALYSIS

The probabilistic seismic hazard assessment (PSHA) of Pakistan is carried out by using the USGS PSHA software for making and updating the US NSHM in accordance with Frankel (1995) spatially smoothed gridded-seismicity, (Harmsen, 2007). There are three broad classes of earthquake sources defined in USGS PSHA: (1) background or gridded sources, (2) crustal fault sources, and (3) subduction sources. Contour maps have been developed from mean PGA for 10% and 2% PE in 50 years. The maps are shown in Fig. 7. These seismic hazard maps are based on a reference site condition that is specified to be the boundary between NEHRP classes B and C (rock site), with an average shear-wave velocity in the upper 30 m of the crust of 760 m/s. PGA across Pakistan is in the range of 5-97% g corresponding to the 475 year return period and in the range of 8-169% g corresponding to the 2475 year return period.

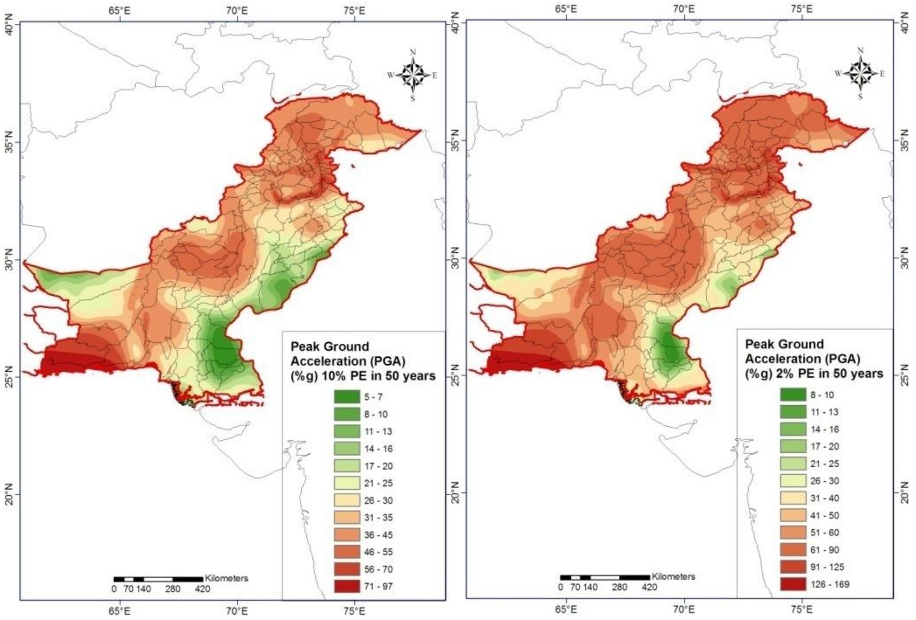

Figure 7. Map of peak ground acceleration (PGA) for 10% PE in 50 years and 2% PE in 50 years in Pakistan in standard gravity (% g)

Hazard in northwest, Azad Jammu Kashmir and western Pakistan is controlled by faults and seismicity and in southwestern Pakistan is by the MSZ. Eastern Pakistan has the least contribution to seismic hazard. Figure 8 show the comparison of PGA maps with 10% PE in 50 years developed by GSHAP (1999), NESPAK (2007), and this study. Although the variation pattern of seismic hazard in this study is somewhat similar to that of past studies, the hazard level is in general higher. Relatively high hazard can be observed at locations near active faults. The comparison also shows that the PGA values for Peshawar and and Islamabad, for example, in this study is higher than those of the other studies as the current study is carried out by using spatially-smoothed gridded seismicity approach, In addition, crustal faults and a subduction zone known as Makran are modelled as seismic sources explicitly with most updated GMPEs.

7. CONCLUSION

This article presents the PSHA of Pakistan carried out by using three model of seismic sources, i.e.

spatially smoothed gridded seismicity (Two BG seismicity with one including three depth intervals of seismicity and the other only shallow depth in area of mapped faults), crustal-fault models (thirteen crustal faults), and subduction source model, and newly recompiled earthquake catalogue. Epistemic uncertainties are taken into account by using the CE and the GR magnitude-frequency models, M_{max}, crustal fault slip rates, three NGA, two intermediate-depths and three subduction GMPEs. With all these new improvements, the resulting maps in this study are believed to represent with currently existing data and most recent computerized data interpretation, the seismic hazard of Pakistan has been updated. Nevertheless, the authors do recognize that more studies, particularly paleoseismic investigation of crustal faults, are required to verify the assumed characteristics of crustal faults. Strong ground motion records for earthquakes in this region would also be essential to make a more prudent choice of GMPEs. In summary, the hazard maps presented here will certainly change in the future when more information on the aforementioned issues becomes available.

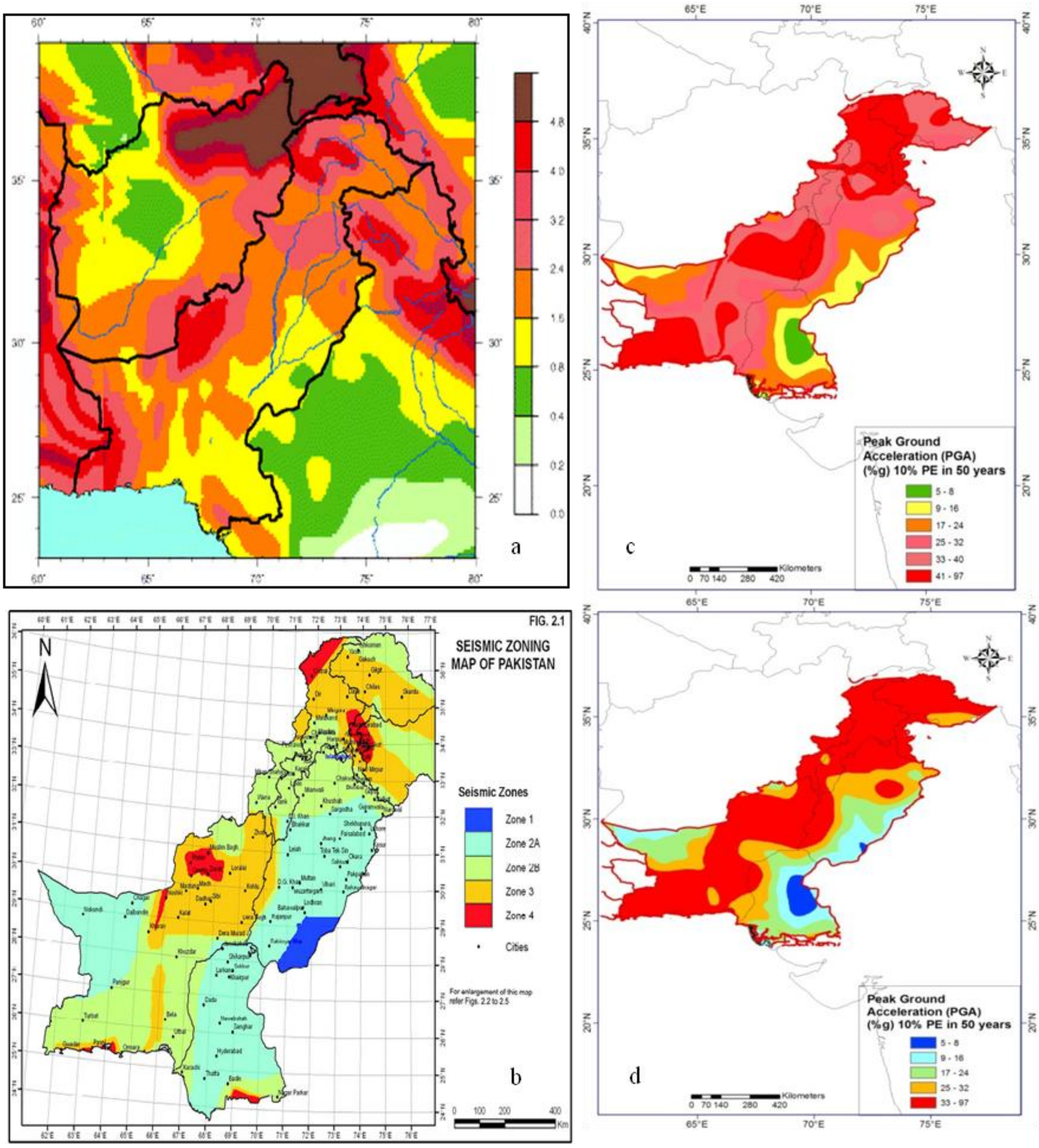

Figure 8 Comparison of PGA maps with 10% PE in 50 years developed by (a) GSHAP 1999, (b) NESPAK 2007 , (c) and (d) This Study—2012

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