Jour. Geol. Soc. India (2022) 98:1308-1319
https://doi.org/10.1007/s12594-022-2167-y

ORIGINAL ARTICLE

Probabilistic Seismic Hazard Analysis of Hazara Kashmir Syntaxes and its Surrounding

Syed Fahad Hussain Shah[a,b*], Chen Ningsheng[a], Ahmad Hammad Khaliq[c], Mehtab Alam[a,b], Hilal Ahmad[a,b], Mahfuzur Rahman[a,b,d]

[a]Key Laboratory for Mountain Hazards and Earth Surface Process, Institute of Mountain Hazards and Environment (IMHE), Chinese Academy of Sciences (CAS), Chengdu 610041, P.R. China
[b]University of Chinese Academy of Sciences (UCAS), Beijing 100049, China
[c]Institute of Geology, University of Azad Jammu and Kashmir, Azad Jammu and Kashmir, Pakistan
[d] Department of Civil Engineering, International University of Business Agriculture and Technology (IUBAT), Dhaka 1230, Bangladesh
E-mail: *fahadshahsyed@gmail.com*; chennsh@imde.ac.cn; ahmadhammad@ajku.edu.pk; engr_mehtab@yahoo.com; geohilal.ahmad0343@hotmail.com; mfz.rahman@iubat.edu*

Received: 31 December 2020; Revised form Accepted: 5 August 2021

ABSTRACT

The Hazara Kashmir syntaxes (HKS) is located in the western Himalayas in Pakistan that marks the easternmost proximity of the western Himalayan mountain system and is regarded as one of the most tectonically active domains of the world. In this study, the seismic ground motion parameters have been calculated for Hazara Kashmir syntaxes and its surrounding. The seismic hazard parameters were computed using probabilistic seismic hazard analysis (PSHA) and the standard Cornell–McGuire method at each grid spacing of 0.1° × 0.1°. This study encompasses the seismic records of the historical and instrumental database to establish the recurrence relationship based on an appropriate ground motion prediction equation (GMPE). Recently developed, the Boore and Atkinson (2008) next-generation attenuation (NGA) and Akkar and Bommer (2007) attenuation relationships were adopted for hazard computation. The resultant peak ground acceleration (PGA) maps and spectral intensity curves at T = 0.05 to T = 3, for 100, 250, 475, 1000, and 2500 year return periods have been estimated at bedrock level. This study concludes that the seismic provision for the building code of Pakistan needs to be revised and updated.

INTRODUCTION

The geographic location of Pakistan is considered to be one of the most seismically active regions in the world as it is home to three major mountain systems, including the Karakorum, Hindukush, and Himalayas. In plate tectonics, the Himalayan orogeny is a prime example of continental collision. Geographically, the western Himalayas of north Pakistan marks the northwestern proximity of the main Himalayas orogenic system (DiPietro and Pogue 2004) and is amongst the most seismically active intercontinental domains of the world (Monalisa, Khwaja et al. 2007). Northern Pakistan is also a location for the convergence of three major tectonic plates. These exceptional tectonic settings indicate a higher probability of seismicity; making the country vulnerable to life losses and infrastructural damages due to unplanned urbanization and poor engineering practices for infrastructural development. Furthermore, the presence of tectonically active elements, including the MBT, main mantle thrust (MMT), main Karakorum thrust (MKT), salt range thrust (SRT), and Chamman transform fault are the potential locations for future seismicity in and around Pakistan.

Considering the efforts to mitigate the seismic hazards, the building code of Pakistan (BCP) (1986) introduced the seismic hazard assessment (SHA), but the first effort for PSHA of Pakistan is made by (Zhang, Yang et al. 1999) under the umbrella of the Global Hazard Assessment Program. After the 2005 Kashmir earthquake, the BCP (2007) introduced PSHA based zoning map of Pakistan along with the seismic hazard provisions for the building code and placed the HKS and adjoining area under seismic zone 3 and 4, the area with a PGA ranges from 0.24 to > 0.32g. Following the hazard assessment work, Monalisa, Khwaja et al. (2007) utilized the Ambraseys et al. (1996) and Boore, Joyner et al. (1997) attenuation relations to produce the peak ground acceleration (PGA) curve for major cities in north Pakistan, including Kaghan, Muzaffarabad, and Islamabad. Later 2010, Hashash, Kim et al. (2012), Rafi, Lindholm et al. (2012), and Zaman, Ornthammarath et al. (2012) contributed to the hazard assessment of Pakistan. Zaman, Ornthammarath et al. (2012) utilized the Frankel (1995) attenuation to generate the hazard map. Other important studies based on PSHA, in and around Pakistan, includes Rahman, Bai et al. (2019), Waseem, Khan et al. (2019), and Sesetyan, Danciu et al. (2018).

All these studies focus on generating the hazard map based on PGA without considering the spectral intensities that can be useful according to if a structure is analyzed with a uniform building code (UBC 97). But with the recommendation of IBC (2015), spectral intensities are of great importance, and hazard analysis cannot be possible without spectral intensities. These studies gap needed to be addressed. Spectral intensities are vital for infrastructural development, mainly for the construction of bridges, high rises, and water reservoirs (Monteiro, Delgado et al. 2015, Hariri-Ardebili and Saouma 2016, Yang, Xie et al. 2019, Sadiq, Muhammad et al. 2021). However, all of the above mentioned studies lack in terms of spectral intensities.

Therefore, the present study provides such an assessment of the seismic hazards by utilizing the PSHA based approach for the major cities inside Hazara Kashmir syntaxes (HKS) region in the western Himalayas of north Pakistan using the recently updated catalog and updated ground motion equations. The PSHA is the most commonly used approach to assess seismic hazard. This approach enables identifying and quantifying the extent and size of a seismic event, deviation in ground motion intensity, and combining these factors to portray the comprehensive framework of the seismic event (Kramer 1996). The results are obtained in the form of a graph between ground motion against the annual rate.

STUDY AREA

Seismo-Tectonic Settings

The Himalayan mountain chain is the result of continental collision between Indian and Eurasian plates since the early Cenozoic (Dewey and Bird 1970; Searle 2019; Treloar, Palin et al. 2019). As the collision time nearly 55Ma ago, the Indian plate has been thrusting below the Eurasian plate with an annual magnitude of 37- 42mm/yr (Chen, Burchfiel et al. 2000; Shen, Zhao et al. 2000). Laterally, the Himalayas are sub-divided into the central Himalayas belt (Nepal, Southern Tibet, and Kumaun), the west-central Himalayas (Chamba, Kashmir, Zanskar in India, and the western syntaxes region of Naran and Nanga Parbat in Pakistan), and western Himalaya (the area west of the Hazara–Kashmir syntaxes in Pakistan; (DiPietro and Pogue 2004).

According to this classification, the study area (HKS) is an integral part of the western Himalayas. The western Himalayas in north Pakistan represent the northwestern edge of the Indian plate and is demarcated by MMT (Tahirkheli, Mattauer et al. 1979, Searle, Khan et al. 1999) in the north and by SRT in the south (Yeats and Lawrence 1982, Kazmi and Jan 1997). Its east-west extent is marked by Hazara Kashmir-Nanga Parbat and Khurram syntaxes, respectively. Along the eastern margin of western Himalaya, the NW-SE orographic trend of the main Himalaya take a loop around the large-scale antiformal structure termed as the Hazara Kashmir syntaxes (Fig. 1) by (Calkins et al. 1975; Bossart, Dietrich et al. 1988).

Generally, along the entire Himalayan orogenic belt, approximately 900 km long seismicity zones extend from Indus Kohistan seismic zone (IKSZ) in north Pakistan to Nepal (Seeber, Armbruster et al. 1981, Pandey, Tandukar et al. 1995). Hazara lower seismic zone (HLSZ) and IKSZ in the internal domain of the system indicate the incidence of shallow earthquakes of 10 to 50 km in depth along crustal faults (Jadoon, Hinderer et al. 2015). The region is dominated by strong decoupling at depth, with restoration and occasional discharge of accumulated stress in the form of great earthquakes (Jadoon, Hinderer et al. 2015). This region has been witnessed major disastrous earthquakes, including the Kangra earthquake (1905) and Kashmir earthquake (2005) of magnitudes Mw = 7.8 and 7.6, respectively, and a number of earthquakes with moderate magnitudes such as the Chamba earthquake (1945, mb = 6.5), Kinnaur earthquake (mb = 6.5), Dharamsala earthquake (1986, mb = 5.7), Uttarkashi (1991, mb = 6.4), and Chamoli (1999, mb = 6.8). The instrumental seismicity database has also classified the zone as the elastic strain accumulation region and can generate a major earthquake (Umesh and Chandra 1975, Ambraseys, Lensen et al. 1981). The GPS records of the Kangra earthquake (1905) and Nepal indicate that the Himalayan front is locked by the southern expansion of a 100 km broad section with a minor amount of convergence (Bendick, Bilham et al. 2000, Banerjee and Burgman 2002, Bettinelli, Avouac et al. 2006). The rupturing along this segment resulted in the generation of strong earthquakes (Bendick,

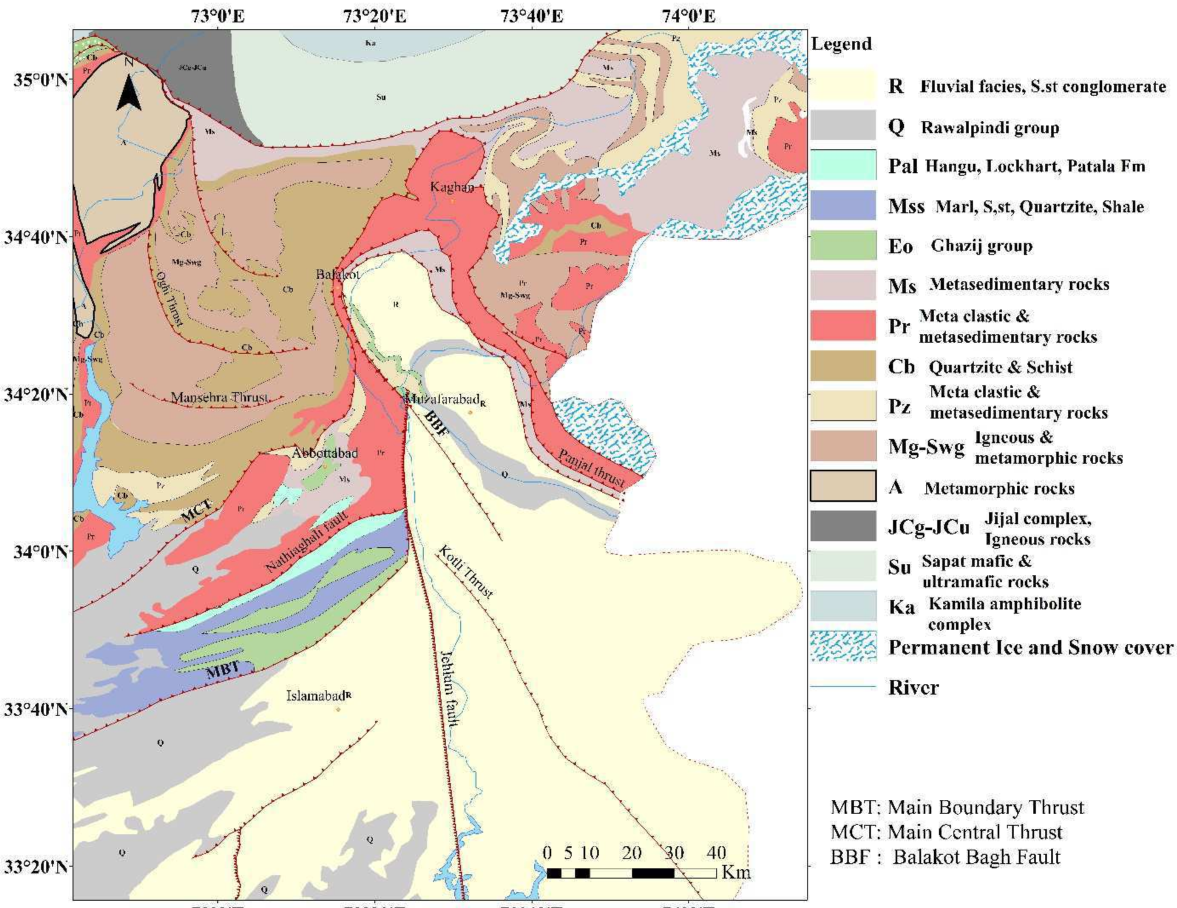

Fig. 1. Geologic and Tectonic map of the study area, HKS (Modified from Khan and Searle, 1997)

Bilham et al. 2000). From 1897-1952, 14 major earthquake events are experienced by the Himalayan mountain belt with a magnitude greater than 7.5, of which five events with magnitude ≥8 (Monalisa, Khwaja et al. 2007). The PGA recorded during the 1897 earthquake was more than 1 g. Northern Pakistan experienced frequent seismic events during the last five decades, including the Pattan earthquake (1974) and Rawalpindi earthquake (1977) with a recorded magnitude of 6.0 and 5.5 mb. These two events are the largest recorded earthquake events in adjoining Hazara Kashmir syntaxes. The main boundary thrust and main mantle thrust are two well-known seismically active fault systems that have the potential to generate medium to large earth-quakes (Umesh and Chandra 1975; Ambraseys, Lensen et al. 1981). It has been assumed that such an earthquake of magnitude equivalent to the disastrous Kangra earthquake of 1905, the death tolls could climb more than 80,000 (Arya 1990). This speculation has been proved to some extent during the 2005 Kashmir earthquake with magnitude of 7.6, a vast region of HKS and fatalities have touched a number of 75000 (Monalisa, Khwaja et al. 2007).

Geological and Structural Setting

The study area is located within the HKS region of the western Himalayas, surrounded by a complex tectonic setting, dominantly active thrusting and deformation. Based on the structural setting (Fig. 1), the HKS is divided into three main components. The eastern limb, the western limb and the syntaxial zone (Calkins, JA et al. 1975). The eastern limb of HKS originated from the Kashmir along Pir Panjal Range and continued northward up to Balakot, where it took a sharp bend in the regional trend toward the southwest and followed along its western limb towards Muzaffarabad. The syntaxes possess a sequence of multiplex nappes varying from Precambrian to Mesozoic formations. Deeply buried Murree Formation of Miocene age is widely distributed and overlain by Kamlial Formation in the south of Muzaffarabad.

Further toward the south, it is overlain by the younger Siwalik Group of Miocene to Pleistocene (Bossart, Dietrich et al. 1988). Around Muzaffarabad and further toward the north in Balakot, Precambrian Muzaffarabad Formation and Paleocene marine sediments underlie Murree Formation (Calkins, JA et al. 1975). The Panjal (PT) and

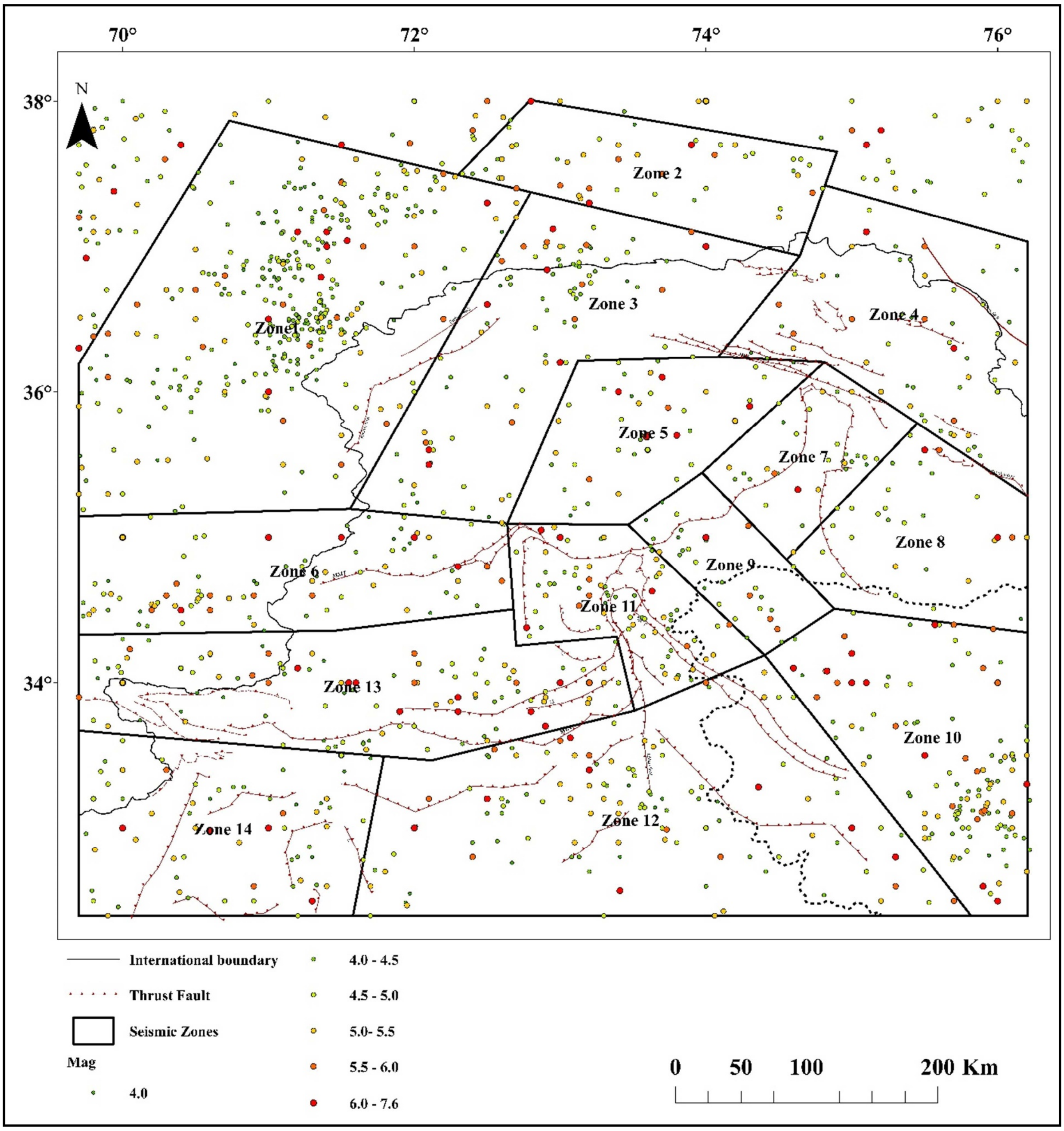

Fig.2. Earthquake distribution and seismic zonation map of North Pakistan

Murree thrust (MT) or MBT (Kazmi and Jan 1997) runs parallel to each other and truncate the eastern limb of HKS. The former comprised of Precambrian Salkhala Formation and Permian Panjal volcanic in its hanging wall, while the latter abuts the Mesozoic and earlier rocks against Murree Formation of Miocene age along the eastern limb of HKS (Kazmi and Jan 1997). The PT bifurcates from MBT along the western limb of HKS about 6km south of Balakot and continued along the western boundary of GHS. In contrast, after separating from PT, MBT continued toward the southeast up to Muzaffarabad and then southward to Kohala and mark the eastern proximity of GHS (Kazmi and Jan 1997). To the north, the HKS bends northwestward and continues into Kaghan and further into the Naga Parbat- Haramosh region of western Himalayas, where some workers call it "the Nanga Parbat syntaxes" (Coward and Butler 1985).

MATERIALS AND METHODS

Data Acquisition

Seismic Catalog Compilation

Notably, a complete earthquake catalog is required to carry out PSHA. Earthquake catalog is globally used the information to define the seismic parameters, source seismicity, and establish the recurrence law for hazard assessment. There is no complete seismicity record available for north Pakistan, therefore to develop the catalog for this study, historical and instrumental data is acquired from various national and international dataset network, including the United States National Earthquake Information Centre (NEIC), International Seismological Centre (ISC) and Pakistan Meteorological Department (PMD). The instrumental data is combined with historical records from other published literature including (Bilham 1999, Ambraseys and Bilham 2003, Bilham, Lodi et al. 2007, Monalisa, Khwaja et al. 2007) to compile a complete catalog for the study area, between longitude 69.70-76.20 and latitude 32.40-38.00 (Fig. 2).

As discussed earlier, the HKS is located on the edge of tectonic boundaries, and earthquakes with small magnitude are frequent. These small earthquakes have no potential impact on engineering structures; therefore, the minimum threshold value is 4.0Mw.

Seismic Catalog Processing

The compiled catalog was carefully examined and compiled from historical, local earthquake agencies (PMD, MSSP, WAPDA) and International recording agencies (USGS, BAAS, ISS, ISC) with massive duplications. To avoid such duplications, the methodology adopted by Khaliq, Waseem et al. (2019) Bhatti, Hassan et al. (2011), was used which suggests the processing of catalogs by removing seismic events based on locality time of occurrence. Seismic catalog processing further removal of duplication errors as under:

- The declustering method of Gardner and Knopoff (1974) was used to remove fore and aftershocks.
- Events > 100 km in depth are rarely effective in catastrophic intensities, these were filtered out.
- Completeness of year analysis for earthquake events.

The processing of earthquakes led to the selection of a total of 1505 events out of 10,506 events. The depth criteria were set up to 100 km, as the shallow earthquakes are more likely to cause severe destruction. The cumulative visual technique introduced by Tinti and Mulargia (1985) is adopted to perform the completeness of year analysis. This technique involves generating the graph of earthquake cumulative number and year from the starting time of catalog for various magnitude classes. The completion period is for a given magnitude range is from the earliest year when the slope on the graph is an approximately straight line. (Fig. 3, Table. 1) The magnitude was classified into a range of 4.0–4.5, 4.5–5.0, 5.0–5.5, 5.5–6.0, 6.0–6.5, 6.5–7.0, and ≥7.0 to point out the completion period. The minimum threshold magnitude was set at 4 as a magnitude lower than 4 is usually missing from the available catalog.

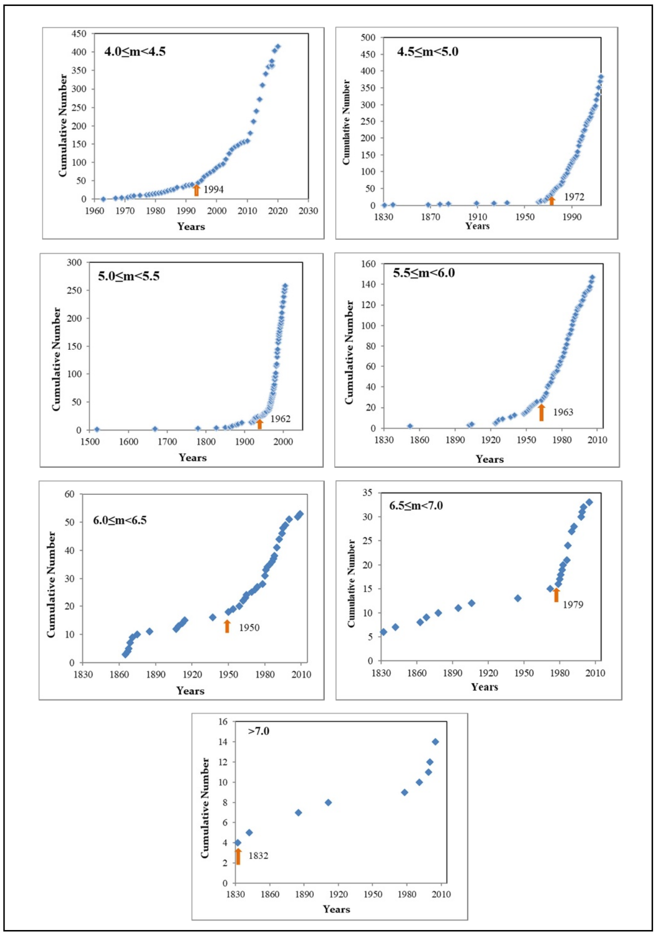

Fig.3. Completeness of year analysis using VCM.

Table 1. Year of Completion analysis for various magnitude classes.

S.no	Earthquake Magnitude Range	Year of Completion
1	4.0 ≤ m < 4.5	1994
2	4.5 ≤ m < 5.0	1972
3	5.0 ≤ m < 5.5	1962
4	5.5 ≤ m < 6.0	1963
5	6.0 ≤ m < 6.5	1950
6	6.5 ≤ m < 7.0	1979
7	> 7.0	1832

Magnitude Homogenization

The recorded earthquake events have been reported on different magnitude scales by different resources, a catalog was processed to obtain the uniform magnitude scale for all reported events. The compiled catalog constitutes events of differing magnitudes type, including surface wave (Ms), body wave (Mb), and local magnitude (ML) scales.

These magnitudes were converted to the moment as the data has been collected from different agencies. This data set was converted to a uniform moment magnitude scale (Mw) by using the empirical relations mentioned below:

- **M_b to M_w** (Scordilis 2006)

$$M_w = 0.85\, M_b + 1.03 \; (3.0 \le M_b \le 6.1) \quad (1)$$

- M_b **to Mw** (Scordilis 2006)

$$M_w = 0.67\ M_s + 2.07\ (3.0 \le M_s \le 6.1) \quad (2)$$

$$M_s = 0.99\ M_s + 0.08\ (6.2 \le M_s \le 8.2) \quad (3)$$

- M_L **to** M_w (Ambraseys 1990)

$$0.87\ M_L - 0.58\ M_s \quad (4)$$

$$Log\ M_o = 19.24 + M_s\ (M_s < 5.3) \quad (5)$$

$$Log\ M_o = 15.94 + 1.5\ M_s\ (M_s > 6.2) \quad (6)$$

$$M_w = 2/3\ log\ M_o - 10.73 \quad (7)$$

Characterization of Seismic Source Zones

To evaluate the seismic hazard, seismic zonation is of known importance. Cornell (1968) and McGuire (1976) approach for the hazard assessment was adopted. This approach defines the seismic source zone based on uniform seismicity. Seismic source zones are geographical representations with have the potential for generating earthquakes. In concern with Pakistan, little work has been done for the classification of seismic sources. Due to uncertainty in associating the earthquake to a particular fault, line sources were not modeled. Only area polygons were considered seismic source zones, and an area of 250-300 km around the HKS is considered for the study. The earthquake events selected for this study are up to 100km in depth. Aerial zones are considered as seismic sources and modeled. The quality of seismic data in Pakistan prior to the 1970s is poor and incomplete; therefore, just seismicity data is available for zoning that often leads to ambiguous results.

In this study, the seismic source zones are assigned based on seismicity record combined with the tectonic setting and assembly of fault in a specific tectonic zone. In Pakistan, this approach was first introduced during the BCP study 2007, and later Khan, Javed et al. (2011) refined it. This approach is utilized, and the study area is divided into 14 distinct seismic zones. (Fig. 2, Table 2).

Seismicity Parameters

Gutenberg–Richter (G–R) Law (Gutenberg and Richter 1944) proposed an empirical relation to establishing the relationship between earthquake magnitude and frequency to calculate the mean annual exceedance rate (ëm) and 'b' value. This empirical relation suggests a higher frequency for smaller magnitude and a lower frequency for a large earthquake. The mean annual exceedance rate (ëm) is the total number of seismic events annually, with the magnitude exceeding or equal to 'M'. The Gutenberg–Richter relation is expressed as:

$$\log N(M) = a - bM \quad (8)$$

where, N is the total number of earthquake events per year, with magnitude greater than or equal to specific magnitude M. Exponentially, it can be written as:

$$\lambda m = 10^{a-bM} \text{ or } \lambda m = \exp(\alpha - \beta M) \quad (9)$$

where, α = a ln (10) and β = b ln (10) in above equation. This equation shows the exponential distribution of earthquakes and covers the magnitude range from $-\infty$ to $+\infty$ (Kramer 1996). The term 'a' defines the seismicity of a specific zone, and 'b' refers to the relative likelihood from smaller to larger earthquakes. If the 'b' value decreases, there will be an increase in the likelihood of a larger earthquake. The seismic parameters for each aerial source are calculated using Mat lab software (Z-map extension) (Table 2). The temporal distribution of earthquakes in the area of interest defines the earthquake recurrence model first introduced by Gutenberg and Richter (1944) in the logarithmic relationship that is used in PSHA. This earthquake recurrence model gives us the frequency of events for a threshold magnitude.

The software utilizes the Gutenberg–Richter (G–R) law to establish the earthquake magnitude and frequency relation to find the mean exceedance rate (λm) and 'b' value (Eq. 8). (Weichert 1980) proposed the maximum likelihood method and is used to determine the 'a' and 'b' value for aerial seismic zones in Northern Pakistan.

The 'b' value of various zones reflects the probability of an earthquake. The zones, including Kashmir-Besal seismic zone, Eastern Kashmir Himalaya zone, Hazara-Kashmir Syntaxial zone, Punjab MBT Seismic zone, and Peshawar-Hazara Seismic zone, have a lower trend for 'b' value. While from the tectonic and earthquake distribution map, it is obvious that the seismic events in these zones are higher in number with a potential magnitude. And strong magnitude earthquakes (M>5) are more frequent since 2010 compared to previous decades.

Ground Motion Prediction Equations (GMPEs)

The GMPE is a mathematically derived empirical relationship utilized to measure the ground vibration parameters such as PGV, PGA, and SA for various periods. A number of variables are considered for computing the ground motion parameters, including earthquake magnitude, focal depth, fault mechanism, travel path, and distance from the source to site.

Developing a regional scale attenuation model requires a bulk amount of strong-motion data. Unfortunately, strong motion data is available for limited regions. This is a major obstacle to formulate

Table 2. Earthquake aerial sources zone parameters used for the computations of hazard for the study area where, λ the exceedance rate with threshold magnitude 4.0.

S. no.	Seismic Source Zones	No. of events	Mmin	Mmax	a value	b value	Beta	Lambda λ
1	Hindukush-Chitral Seismic Zone	332	4.0	7.3	5.37	0.7	1.61	0.94
2	Pamir Seismic Zone	47	4.0	7.6	5.61	0.83	1.91	0.83
3	Karakorum Seismic Zone	97	4.0	7.4	4.52	0.59	1.36	0.77
4	Indus-Kohistan Seismic Zone	65	4.0	6.4	8.28	1.32	3.04	1.10
5	Eastern Kohistan Seismic Zone	48	4.0	6.5	4.92	0.71	1.64	0.73
6	Peshawar-Hazara Seismic Zone	90	4.0	7.4	3.66	0.43	0.99	0.66
7	Nanga-Parbat Seismic Zone	31	4.0	6.1	5.05	0.81	1.87	0.59
8	Deosai Seismic Zone	37	4.0	6.2	5.68	0.9	2.07	0.73
9	Kashmir-Besal Seismic Zone	34	4.0	7.2	3.79	0.56	1.29	0.44
10	Eastern Kashmir Himalaya Zone	137	4.0	7.6	4.56	0.56	1.29	0.84
11	Hazara-Kashmir Syntaxial Zone	69	4.0	7.6	4.51	0.62	1.43	0.71
12	N-E Potowar Zone	134	4.0	7	5.50	0.75	1.73	0.92
13	Punjab MBT Seismic Zone	120	4.0	7.4	3.73	0.41	0.94	0.74
14	N-W Potowar Zone	79	4.0	6.6	5.72	0.75	1.73	1.00

GMPEs applicable to the tectonic settings of Pakistan. Therefore, the only viable option is to select the attenuation relation derived for the region with geological and tectonic settings identical to Pakistan. In this study, the (Boore and Atkinson 2008) NGA (next generation attenuation) and (Akkar and Bommer 2007) attenuation relationships are adopted for computation of ground motion parameters. These GMPEs are developed for the regions with shallow seismicity, similar to Northern Pakistan.

Boore and Atkinson 2008 NGA Relationship

This equation is significantly modified from GMPEs developed by (Boore, Joyner et al. 1997). The generalized form of attenuation relationship (10) is mentioned below:

$$\ln Y = M * F_M + F_D(R_{JB}, M) + F_S(V_{S30}, R_{JB}, M) + \varepsilon\sigma_T \quad (10)$$

In this equation, Y represents earthquake intensity, F_M is a magnitude scale factor, F_D is distance function, F_S is site amplification factor, M is the moment magnitude, V_{S30} is the average shear velocity in the upper 30m of crust, the fractional standard deviation for predicted values of lower and higher lnY from the mean value and coefficient σ_T is period dependent is computed as $\sigma_T = \sqrt{(\sigma_2 + \tau^2)}$ where τ is the intra-event aleatory uncertainty and σ is the inter-event aleatory uncertainty.

Akkar and Bommer (2010) GMPE

The (Akkar and Bommer 2010) GMPE is published recently and is a modified version of (Akkar and Bommer 2007) is used to compute the PGA, PGV, and SA in the Middle East, the Mediterranean, and Europe (Akkar and Bommer 2007) the tectonic condition similar to the study area.

$$\log (PSA) = b_1 + b_2\mathrm{M} + b_3\mathrm{M}^2 + (b_4 + b_2\mathrm{M}) \log \sqrt{(R_{JB}^2 + b_6^2)} + b_7\mathrm{S_S} + b_8\mathrm{S_A} + b_9\mathrm{F_N} + b_{10}\mathrm{F_R} + \delta \quad (11)$$

Seismic Hazard Analyses

The PSHA is the most commonly used method for hazard analysis during the last 4-5 decades. This method was developed by (Cornell 1968). The Crisis software 2018 (version 18.4.2) has been used for PSHA, as it enables the design of seismic data as Poissonian distribution. Therefore, the Cornell–McGuire (Cornell 1968; McGuire 1976) approach is utilized in recent studies to compute the ground motion parameters with a grid increment of $0.1^o \times 0.1^o$. A maximum magnitude limit (+0.3 to 0.5) is assigned to each aerial zone, based upon the highest recorded magnitude in every source zone.

The logic tree is used to determine the cognitive ambiguity for GMPEs. The logic tree for PSHA is divided into two branches, and GMPE has given equal weight for each source (Fig. 4). The logic tree adopted for this research is similar to the one adopted by Khaliq et al., 2019.

RESULTS AND DISCUSSION

This study is carried out to assess the seismic hazard for northern Pakistan and compute the spectral intensity curves at T = 0.05 to T = 3s, for major cities inside HKS. Using modified areal seismic source zones and seismicity parameters has contributed to the detailed seismic hazard zonation of northern Pakistan. Crisis software 2018 (version 18.4.2) was used to calculate ground motion parameters at each grid spacing of 0.1^o X 0.1^o degrees. The computation results were collected as horizontal PGA values and exported to the geographic information system (ArcGIS v.10.5) to generate hazard maps for return periods of 100, 250, 475,1000, and 2500 years for the whole of northern Pakistan (Fig. 5).

The concept of seismic zoning that confirms the orientation of faults further improves the characterization of seismic parameters and identification of potential movement along the active faults. A delineation of a seismic source is the entity that can generate earthquakes, in combination with the detailed parameters like geology tectonic setting, faults and their kinematics, and seismicity can improve the characterization of the seismic source areas. The seismic provision of BCP (2007) for the definition of seismic source zones is adopted, later these zones were refined by Khan, Javed et al. (2011) following the tectonic setting characterized for Pakistan and their adjoining areas. The present study modified these seismic zones in combination with seismicity and fault parameters. The area of interest is subdivided into 14 zones (Fig. 2), covering the NW region within 250-300 km from the Hazara Kashmir Syntaxes. However, the interrelationship between faults and seismicity is not well constrained because of distribution. Further, the seismic events from outside the buffer zone are eliminated, considered distant earthquakes that did not potentially impact the engineering structures.

The Ground Motion Prediction Equation (GMPE, s) assigned to

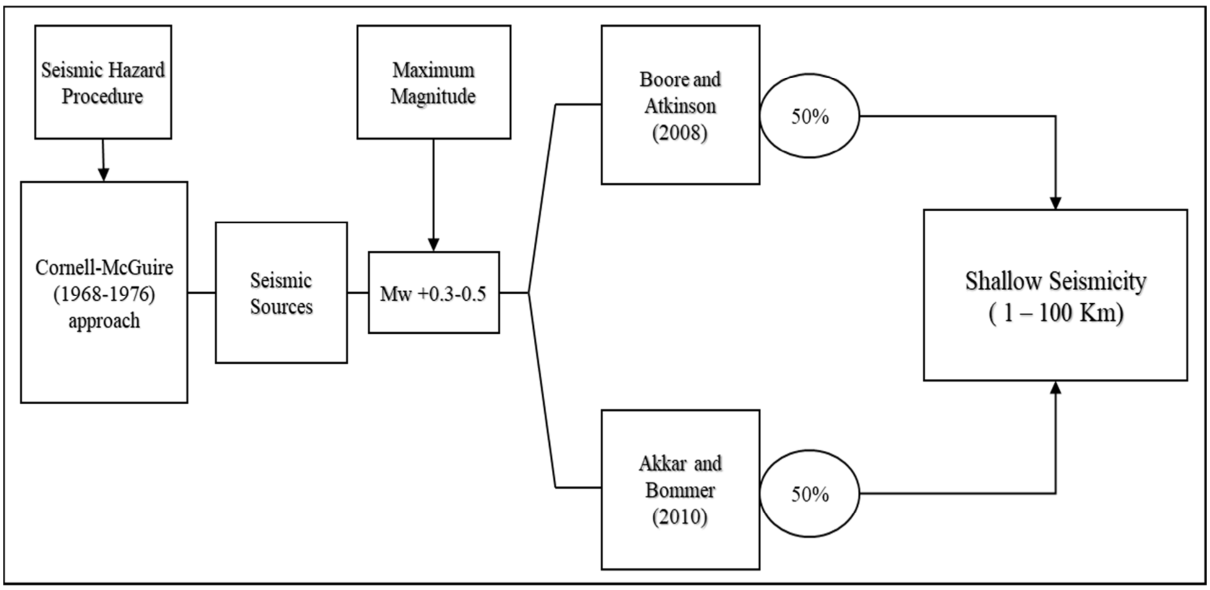

Fig. 4. The logic tree used in PSHA

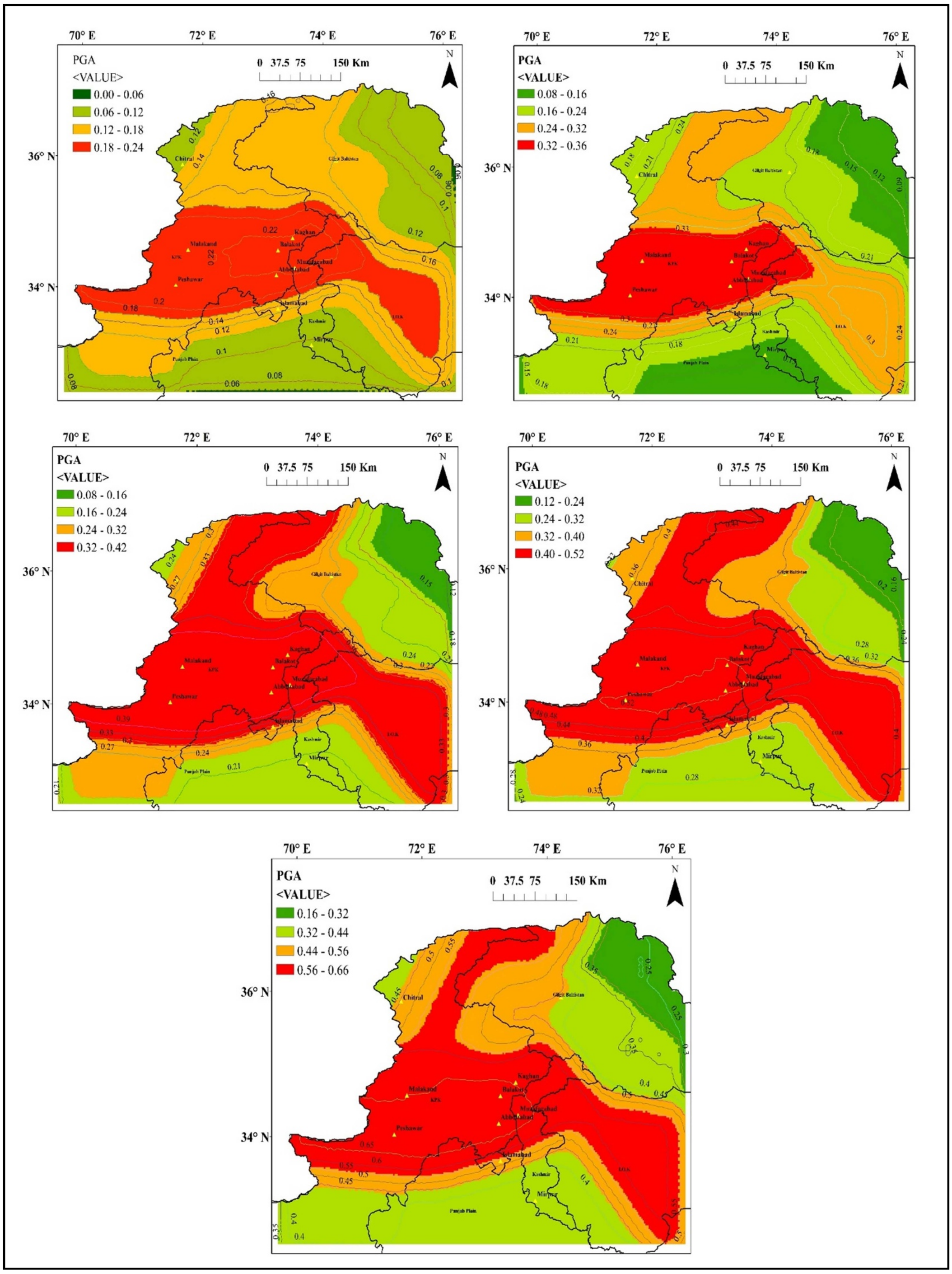

Fig.5. Seismic hazard map of northern Pakistan at 100, 250, 475, 1000 and 2475 years respectively

the defined seismic mentioned in the logic tree. The mathematical expression (Eq. 10 & 11) is input for the Crisis software to compute the seismic hazard. Unfortunately, strong motion data for Pakistan is missing; therefore, the two GMPE, i.e., Boore and Atkinson (2008) and Akkar and Bommer (2010) are preferred for the shallow tectonic setting based on low variability and limited input data parameters in comparison with other developed equation.

Mean annual exceedance rate (ëm), uniform hazard curves, PGA maps, and values comparison of selected cities in HKS at different return periods with a time frame of 50 years are given. (Table 2 & 3, Fig. 6 & 7). This study primarily focuses on PSHA based study for the Hazara Kashmir syntaxes region include Kaghan, Balakot, Muzaffarabad, and Islamabad in northern Pakistan, incorporating all the input parameters describes above. The resultant of seismic hazard analysis is obtained in the form of Uniform hazard spectra (Fig. 7), (Tables 5, 6, 7, 8, and 9) and PGA hazard maps for Kaghan, Balakot,

Table 3. Results of PGA against return period vs PGA value for the major location inside HKS.

Return Period (Tr) in years	Kaghan	Balakot	Muzaffarabad PGA (g)	Islamabad	Abbottabad
100	0.22	0.22	0.22	0.15	0.22
250	0.34	0.35	0.35	0.24	0.35
475	0.41	0.42	0.42	0.32	0.42
1000	0.51	0.52	0.52	0.4	0.52
2500	0.65	0.65	0.66	0.53	0.66

Table 4. Comparison of PGA values calculated by Comparison of PGAs predicted by Monalisa et al. (2007), Hashash et al. (2012b) and present study with a return period of 475 years while PMD and NORSAR (2006) with a return period of 500 years.

Sites	Monalisa et al. (2007)		PMD and NORSAR (2006)	Hashash et al. (2012)	Present Study
	Ambraseys and Simpson (1996)	Boore et al. (1997)	Ambraseys and Simpson (1996)		Boore & Atkinson (2008), Akkar & Bommer (2010)
Kaghan	0.09	0.12	0.20	0.58	0.41
Balakot	-	-	-	-	0.42
Muzaffarabad	0.10	0.13	0.20	0.64	0.42
Islamabad	0.10	0.15	0.20	-	0.32

Table 5. Spectral Intensities of major cities inside HKS at 100 years return period.

Spectral Intensities of major cities inside HKS at 100 years return period					
Cities Spectral Time (sec)	Kaghan	Balakot	Muzaffarabad	Abbottabad	Islamabad
	Spectral Acceleration				
0.00	0.22	0.22	0.22	0.22	0.15
0.05	0.29	0.29	0.29	0.28	0.19
0.10	0.41	0.42	0.42	0.41	0.27
0.20	0.51	0.52	0.52	0.51	0.34
0.30	0.47	0.47	0.48	0.47	0.31
0.40	0.41	0.42	0.42	0.42	0.27
0.50	0.35	0.36	0.36	0.36	0.23
1.00	0.17	0.18	0.18	0.18	0.12
1.50	0.11	0.11	0.12	0.12	0.08
2.00	0.08	0.08	0.08	0.08	0.06
3.00	0.05	0.05	0.05	0.05	0.04

Table 6. Spectral Intensities of major cities inside HKS at 250 years return period.

Spectral Intensities of major cities inside HKS at 250 years return period					
Cities Spectral Time (sec)	Kaghan	Balakot	Muzaffarabad	Abbottabad	Islamabad
	Spectral Acceleration				
0.00	0.34	0.35	0.35	0.35	0.24
0.05	0.42	0.42	0.43	0.42	0.30
0.10	0.64	0.64	0.65	0.64	0.43
0.20	0.78	0.78	0.79	0.79	0.55
0.30	0.74	0.75	0.75	0.75	0.51
0.40	0.66	0.67	0.68	0.68	0.45
0.50	0.57	0.58	0.58	0.58	0.39
1.00	0.29	0.30	0.31	0.31	0.20
1.50	0.20	0.20	0.21	0.21	0.13
2.00	0.14	0.14	0.15	0.15	0.09
3.00	0.08	0.08	0.09	0.09	0.06

Table 7. Spectral Intensities of major cities inside HKS at 475 years return period.

Spectral Intensities of major cities inside HKS at 475 years return period					
Cities Spectral Time (sec)	Kaghan	Balakot	Muzaffarabad	Abbottabad	Islamabad
	Spectral Acceleration				
0.00	0.41	0.42	0.42	0.42	0.32
0.05	0.53	0.54	0.54	0.54	0.39
0.10	0.77	0.77	0.78	0.77	0.58
0.20	1.01	1.02	1.03	1.03	0.73
0.30	0.96	0.98	0.99	0.99	0.69
0.40	0.85	0.87	0.88	0.88	0.62
0.50	0.73	0.74	0.75	0.75	0.54
1.00	0.38	0.39	0.39	0.39	0.28
1.50	0.27	0.29	0.29	0.29	0.19
2.00	0.19	0.20	0.20	0.20	0.14
3.00	0.11	0.11	0.12	0.12	0.08

Table 8. Spectral Intensities of major cities inside HKS at 1000 years return period

Spectral Intensities of major cities inside HKS at 1000 years return period					
Cities Spectral Time (sec)	Kaghan	Balakot	Muzaffarabad	Abbottabad	Islamabad
	Spectral Acceleration				
0.00	0.51	0.52	0.52	0.52	0.40
0.05	0.67	0.68	0.68	0.68	0.51
0.10	0.96	0.97	0.98	0.97	0.74
0.20	1.26	1.27	1.28	1.28	0.97
0.30	1.22	1.23	1.24	1.24	0.93
0.40	1.11	1.12	1.13	1.14	0.83
0.50	0.95	0.97	0.98	0.99	0.72
1.00	0.49	0.50	0.51	0.51	0.38
1.50	0.36	0.37	0.37	0.38	0.28
2.00	0.25	0.26	0.27	0.27	0.19
3.00	0.15	0.15	0.16	0.16	0.11

Table 9. Spectral Intensities of major cities inside HKS at 2500 years return period

Spectral Intensities of major cities inside HKS at 2500 years return period					
Cities Spectral Time (sec)	Kaghan	Balakot	Muzaffarabad	Abbottabad	Islamabad
	Spectral Acceleration				
0.00	0.65	0.65	0.66	0.66	0.53
0.05	0.82	0.83	0.84	0.84	0.68
0.10	1.21	1.22	1.23	1.23	0.98
0.20	1.58	1.60	1.61	1.61	1.29
0.30	1.52	1.54	1.55	1.56	1.24
0.40	1.38	1.40	1.40	1.41	1.14
0.50	1.21	1.22	1.23	1.24	0.99
1.00	0.65	0.66	0.67	0.67	0.52
1.50	0.47	0.49	0.50	0.50	0.38
2.00	0.34	0.35	0.36	0.36	0.27
3.00	0.20	0.21	0.21	0.21	0.16

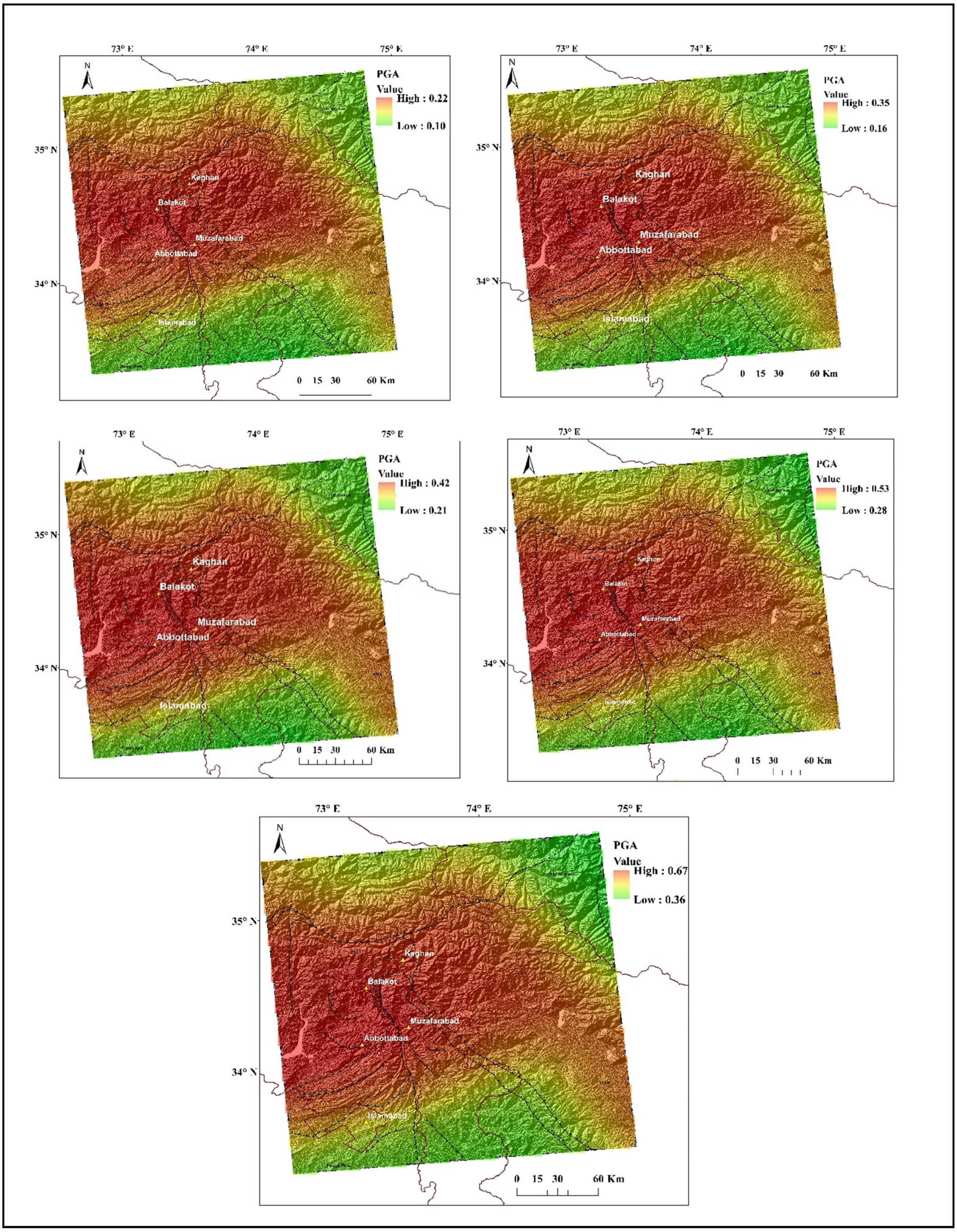

Fig.6. PGA map of HKS with return period of 100, 250, 475, 1000 and 2500 years.

Muzaffarabad, and Islamabad at different return period of 100, 250, 475, 1000 and 2500 years. The computed hazard contour maps of Hazara Kashmir Syntaxes and Northern Pakistan PGA values at 100, 250, 475, 1000, and 2500 return periods are given in Figs. 6.

PGA values ranges for Balakot (0.42 g), Kaghan (0.41 g), Muzaffarabad (0.42 g) and Islamabad (0.32 g) for a return period of 475y and Balakot (0.65 g), Kaghan (0.65 g), Muzaffarabad (0.66 g) and Islamabad (0.53 g) for a return period of 2500y (Table 3).

For the first time, specific site hazard spectra are generated for major cities inside Hazara Kashmir syntaxes. The resultant PGA values are also compared with (NORSAR 2006, Monalisa, Khwaja et al. 2007) and (Hashash, Kim et al. 2012) at specific computed sites (Table 4). The values are much higher than those of Monalisa, Khwaja et al. (2007) and NORSAR (2006) but slightly lower than Hashash, Kim et al. (2012). (Hashash, Kim et al. 2012) have considered the earthquakes of depth up to 35 km and used the discrete fault-based approach. In this study, the events with depth up to 100Km are added, and aerial source-based computation is employed. While in comparison to the

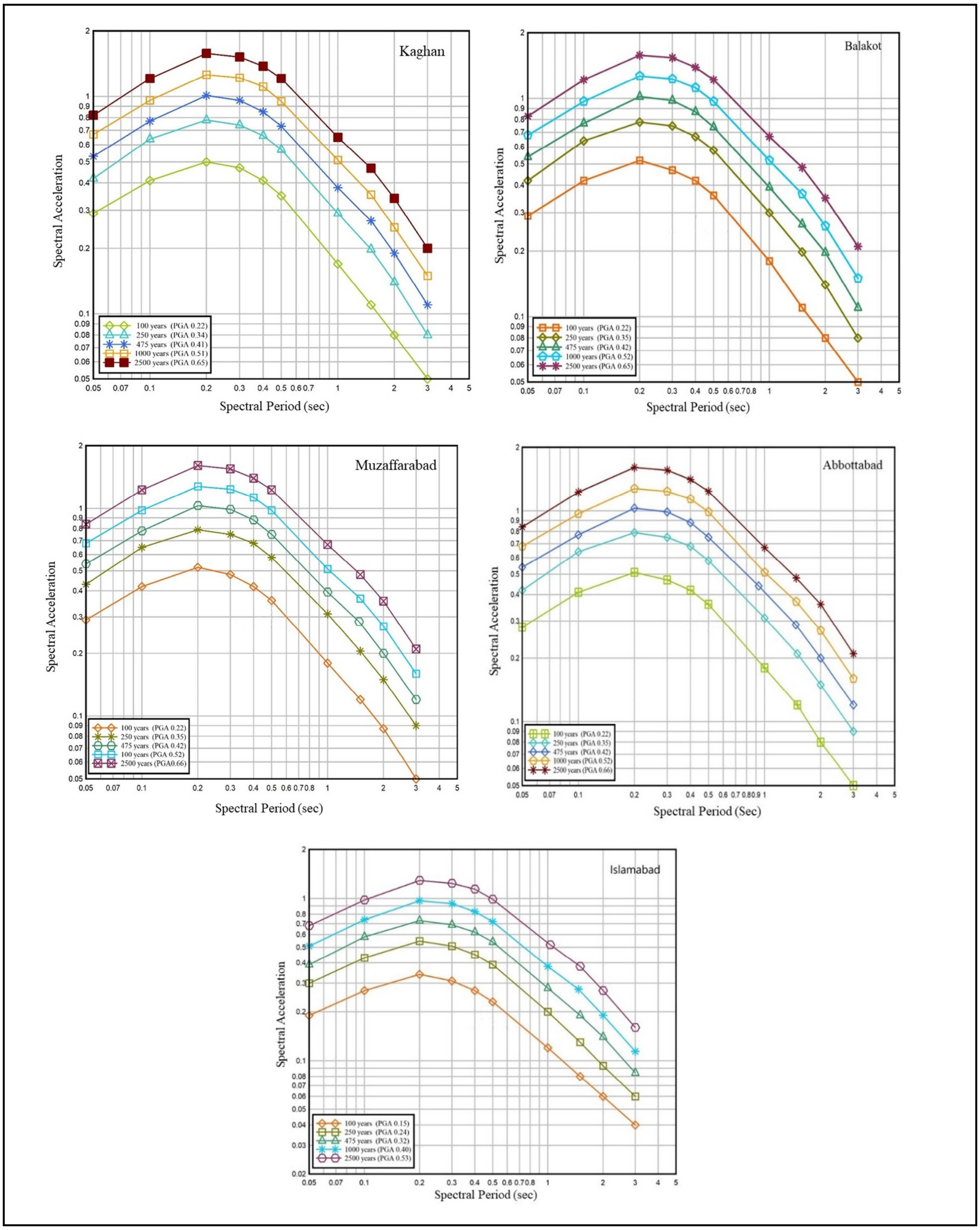

Fig.7. Uniform hazard spectra (UHS) of major cities inside HKS.

seismic provision of the building code of Pakistan (BCP 2007), it completely underestimates the ground motion in northern Pakistan. The hazard maps and specific site spectra picture the ground motion that is much higher than that.

CONCLUSIONS

It is still unrealistic to predict the exact timing of an earthquake, and engineering practices still rely upon the seismic hazard analysis to cope with the earthquake disaster by practicing advanced aseismic designs of structures. So, it is suggested that the building code must be updated, and the design criteria should be based on realistic figures. This study presents an updated seismic hazard map of northern Pakistan for the return period of 100, 250, 475, 1000, and 2500 years with a time frame t = 50 years. The spectral intensities are also proposed in this study with 11 spectral ordinates. This study further suggests the following results:

1. The PGA map and resultant hazard spectra suggest that the Hazara Kashmir syntaxes zone, Peshawar Hazara seismic zone, Punjab MBT seismic zone, and Indus Kohistan seismic zone is more prone to seismic hazard.
2. The cities of Balakot and Muzaffarabad are highly exposed to the seismic hazard (with a PGA value of 0.42 with 475 years

return period), in comparison with other cities in and around HKS.

3. Spectral intensities values of major cities inside HKS (i.e., Balakot, Kaghan, Muzaffarabad, Abbottabad, and Islamabad) are the major contribution of the present study and fulfill the recommendations of IBC (2015). Resultant spectral acceleration maps may provide a base for the aseismic design of building design in Pakistan, in line with IBC's (2015) recommendations.

References

Akkar, S. and Bommer, J.J. (2007) Prediction of elastic displacement response spectra in Europe and the Middle East. Earthquake Eng. Struct. Dynam., v.36(10), pp.1275-1301.

Akkar, S. and Bommer, J.J. (2010) Empirical equations for the prediction of PGA, PGV, and spectral accelerations in Europe, the Mediterranean region, and the Middle East. Seismol. Res. Lett., v.81(2), pp.195-206.

Ambraseys et al. (1996) Prediction of vertical response spectra in Europe. Earthquake Eng. Struct. Dynam., v.25(4), pp.401-412.

Ambraseys, N. (1990). "Uniform magnitude re evaluation of European earthquakes associated with strong motion records." Earthquake Eng. Struct. Dynam., v.19(1), pp.1-20.

Ambraseys, N. and Bilham, R. (2003) Earthquakes and associated deformation in northern Baluchistan 1892-2001. Bull. Seismol. Soc. Amer., v.93(4), pp.1573-1605.

Ambraseys, N., Lensen, G., Moinfar, A. and Pennington, W. (1981) The Pattan (Pakistan) earthquake of 28 December 1974: field observations. Quart. Jour. Eng. Geol. Hydrogeol., v.14(1), pp.1-16.

Arya, A. (1990) Damage scenario of a hypothetical 8.0 magnitude earthquake in Kangra region of Himachal Pradesh. Bull. Indian Soc. Earthquake Tech., v.27(3), pp.121-132.

Banerjee, P. and Burgman, R. (2002) Active tectonics of Himalayan Frontal thrust and seismic hazards to Ganga Plain. Geophys. Res. Lett., v.29, pp.301-304.

BCP, S. (2007) Building Codes of Pakistan Seismic Provisions Government of Islamic republic of Pakistan Ministry of Housing and Works, Islamabad.

Bendick, R., Bilham, R., Freymueller, J., Larson, K. and Yin, G. (2000) Geodetic evidence for a low slip rate in the Altyn Tagh fault system. Nature, v.404(6773), pp.69-72.

Bettinelli, P., Avouac, J.-P., Flouzat, M., Jouanne, F., Bollinger, L., Willis, P. and Chitrakar, G.R. (2006) Plate motion of India and interseismic strain in the Nepal Himalaya from GPS and DORIS measurements. Jour. Geodesy, v.80(8-11), pp.567-589.

Bhatti, A.Q., Hassan, S.Z.U., Rafi, Z., Khatoon, Z. and Ali, Q. (2011) Probabilistic seismic hazard analysis of Islamabad, Pakistan. Jour. Asian Earth Sci., v.42(3), pp.468-478.

Bilham, R. (1999) Slip parameters for the Rann of Kachchh, India, 16 June 1819, earthquake, quantified from contemporary accounts. Geol. Soc. London, Spec. Publ., v.146(1), pp.295-319.

Bilham, R., Lodi, S., Hough, S., Bukhary, S., Khan, A.M. and Rafeeqi, S. (2007) Seismic hazard in Karachi, Pakistan: uncertain past, uncertain future. Seismol. Res. Lett., v.78(6), pp.601-613.

Boore, D.M. and Atkinson, G.M. (2008) Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. Earthquake Spectra, v.24(1), pp.99-138.

Boore, D.M., Joyner, W.B. and Fumal, T.E. (1997) Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work. Seismol. Res. Lett., v.68(1), pp.128-153.

Bossart, P., Dietrich, D., Greco, A., Ottiger, R. and Ramsay, J.G. (1988) The tectonic structure of the Hazara Kashmir syntaxis, southern Himalayas, Pakistan. Tectonics, v.7(2), pp.273-297.

Calkins, J.A., Offield, T.W., Abdullah, S.K. and Ali, S.T. (1975) Geology of the Southern Himalaya in Hazara, Pakistan and adjacent areas. USGS Prof. Paper 716-C.

Chen, Z., Burchfiel, B., Liu, Y., King, R., Royden, L., Tang, W., Wang, E., Zhao, J. and Zhang, X. (2000) Global Positioning System measurements from eastern Tibet and their implications for India/Eurasia intercontinental deformation. Jour. Geophys. Res.: Solid Earth, v.105(B7), pp.16215-16227.

Cornell, C.A. (1968) Engineering seismic risk analysis. Bull. Seismol. Soc. Amer., v.58(5), pp.1583-1606.

Coward, M. and Butler, R. (1985) Thrust tectonics and the deep structure of the Pakistan Himalaya. Geology, v.13(6), pp.417-420.

Dewey, J.F. and Bird, J.M. (1970) Mountain belts and the new global tectonics. Jour. Geophys. Res., v.75(14), pp.2625-2647.

DiPietro, J.A. and Pogue, K.R. (2004) Tectonostratigraphic subdivisions of the Himalaya: A view from the west. Tectonics, v.23(5).

Frankel, A. (1995) Mapping seismic hazard in the central and eastern United States. Seismol. Res. Lett., v.66(4), pp.8-21.

Gardner, J. and Knopoff, L. (1974) Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? Bull. Seismol. Soc. Amer., v.64(5), pp.1363-1367.

Gutenberg, B. and Richter, C.F. (1944) Frequency of earthquakes in California. Bull. Seismol. Soc. Amer., v.34(4), pp.185-188.

Hariri-Ardebili, M. and Saouma, V. (2016) Probabilistic seismic demand model and optimal intensity measure for concrete dams. Structural Safety, v.59, pp.67-85.

Hashash, Y.M., Kim, B., Olson, S.M. and Ahmad, I. (2012) Seismic hazard analysis using discrete faults in Northwestern Pakistan: Part II–Results of seismic hazard analysis. Jour. Earthquake Eng., v.16(8), pp.1161-1183.

Jadoon, I.A., Hinderer, M., Kausar, A.B., Qureshi, A.A., Baig, M.S., Basharat, M. and Frisch, W. (2015) Structural interpretation and geo-hazard assessment of a locking line: 2005 Kashmir Earthquake, western Himalayas. Environ. Earth Sci., v.73(11), pp.7587-7602.

Kazmi, A.H. and Jan, M.Q. (1997) Geology and tectonics of Pakistan. Graphic Publishers.

Khaliq, A.H.,M. Waseem, S. Khan, Ahmed, W. and Khan, M.A. (2019) Probabilistic seismic hazard assessment of Peshawar District, Pakistan. Jour. Earth Syst. Sci., v.128(1), pp.1-22.

Khan, M., Javed, M. and Sayab, M. (2011) Fault map and associated database of fault parameters for Pakistan. WP-1 Interim Report, Earthquake model of middle east (EMME) international project.

Kramer, S.L. (1996) Geotechnical earthquake engineering, Pearson Education India.

McGuire, R.K. (1976) FORTRAN computer program for seismic risk analysis, USGS.

Monalisa, A.A. Khwaja and Jan, M.Q. (2007) Seismic hazard assessment of the NW Himalayan fold-and-thrust belt, Pakistan, using probabilistic approach. Jour. Earthquake Eng., v.11(2), pp.257-301.

Monteiro, R., Delgado, R. and Pinho, R. (2015) Using different uncertainty models for seismic assessment of RC bridges. Proceedings of 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2015), Crete Island, Greece.

Norsar, P. (2006) Seismic Hazard Analysis for the Cities of Islamabad and Rawalpindi, 47.

Pandey, M., Tandukar, R., Avouac, J. Lave, J. and Massot, J. (1995) Interseismic strain accumulation on the Himalayan crustal ramp (Nepal). Geophys. Res. Lett., v.22(7), pp.751-754.

Rafi, Z., Lindholm, C., Bungum, H., Laghari, A. and Ahmed, N. (2012) Probabilistic seismic hazard of Pakistan, Azad-Jammu and Kashmir. Natural Hazards, v.61(3), pp.1317-1354.

Rahman, M.M., Bai, L., Khan, N.G. and Li, G. (2019) Probabilistic seismic hazard assessment for Himalayan–tibetan region from historical and instrumental earthquake catalogs. Earthquakes and Multi-hazards Around the Pacific Rim, Vol. II, Springer, pp.161-181.

Sadiq, S., Muhammad, A., Mandokhail, S.-u.J., Rehman, M.-U., Mehtab, A., Muhammad, N. and Adeel, M.B. (2021) Evaluation of Site Amplification Factors for Shallow Rock Sites of Islamabad, Pakistan. Kuwait Jour. Sci., v.48(2).

Scordilis, E. (2006) Empirical global relations converting M S and m b to moment magnitude. Jour. Sseismol., v.10(2), pp.225-236.

Searle, M., Khan, M.A., Fraser, J., Gough, S. and Jan, M. Q. (1999) The tectonic evolution of the Kohistan Karakoram collision belt along the Karakoram Highway transect, north Pakistan. Tectonics, v.18(6), pp.929-949.

Searle, M.P. (2019) Timing of subduction initiation, arc formation, ophiolite obduction and India–Asia collision in the Himalaya. Geol. Soc. London, Spec. Publ., v.483(1), pp.19-37.

Seeber, L., Armbruster, J.G. and Quittmeyer, R.C. (1981) Seismicity and continental subduction in the Himalayan arc. Zagros Hindu Kush Himalaya Geodynamic Evolution, v.3, pp.215-242.

Sesetyan, K., Danciu, L., Tümsa, M.B.D., Giardini, D., Erdik, M., Akkar, S., Gülen, L., Zare, M., Adamia, S. and Ansari, A. (2018) The 2014 seismic hazard model of the Middle East: overview and results. Bull. Earthquake Eng., v.16(8), pp.3535-3566.

Shen, Z.K., Zhao, C., Yin, A., Li, Y., Jackson, D.D., Fang, P. and Dong, D. (2000) Contemporary crustal deformation in east Asia constrained by Global Positioning System measurements. Jour. Geophys. Res.: Solid Earth, v.105(B3), pp.5721-5734.

Tahirkheli, R., Mattauer, M., Proust, F. and Tapponnier, P. (1979) The India Eurasia suture zone in northern Pakistan: Ssynthesis and interpretation of recent data at plate scale. Geodynamics of Pakistan (pp. 125–130). Quetta: Geol. Surv. Pakistan.

Tinti, S. and Mulargia, F. (1985) Completeness analysis of a seismic catalog. Annales Geophysicae (1983).

Treloar, P.J., Palin, R.M. and Searle, M.P. (2019) Towards resolving the metamorphic enigma of the Indian Plate in the NW Himalaya of Pakistan. Geol. Soc. London, Spec. Publ., v.483(1), pp.255-279.

Umesh Chandra (1975) Fault-Plane Solution And Tectonic Implications of the Pattan, Pakistan Earthquake of December 28, 1974. Tectonophysics, v.28(3), pp.T19-T24.

Waseem, M., Khan, M.A. and Khan, S. (2019) Seismic sources for southern Pakistan and seismic hazard assessment of Karachi. Natural Hazards, v.99(1), pp.511-536.

Weichert, D.H. (1980) Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes. Bull. Seismol. Soc. Amer., v.70(4), pp.1337-1346.

Yang, C., Xie, L., Li, A., Jia, J. and Zeng, D. (2019) Ground motion intensity measures for seismically isolated RC tall buildings. Soil Dynamics and Earthquake Eng., v.125, 105727.

Yeats, R. and Lawrence, R. (1982) Tectonics of the Himalayan thrust belt in northern Pakistan. MASC.

Zaman, S., Ornthammarath, T. and Warnitchai, P. (2012) Probabilistic seismic hazard maps for Pakistan. Proc. 15th World Conf. Earthq. Engg. -WCEE.

Zhang, P., Yang, Z.-x., Gupta, H.K., Bhatia, S.C. and Shedlock, K.M. (1999) Global seismic hazard assessment program (GSHAP) in continental Asia. Annali di Geofisica, v.42(6), pp.1167-1190. doi:10.4401/ag-3778.