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Seismic Hazard Maps of Peshawar District for Various Return Periods

Khalid Mahmood[1*], Usman Khan[2], Qaiser Iqbal[3], Naveed Ahmad[4]

[1*]Associate Professor, Department of Civil Engineering, Sarhad University of Science and Information Technology, Peshawar, Pakistan
(Corresponding author Email: khalid.civil@suit.edu.pk; Cell No. +92-3419641590)

[2]Lecturer, Department of Civil Engineering, Sarhad University of Science and Information Technology, Peshawar, Pakistan (malakusman@gmail.com)

[3]Assistant Professor, Department of Civil Engineering, Sarhad University of Science and Information Technology, Peshawar, Pakistan (qi.civil@suit.edu.pk)

[4]Associate Professor, Department of Civil Engineering, University of Engineering and Technology, Peshawar, Pakistan (naveed.ahmad@uetpeshawar.edu.pk)

Abstract:

The probabilistic seismic hazard analysis of Peshawar District has been conducted in for a grid size of 0.01. The seismic sources for the target location are defined as the area polygon with uniform seismicity for which, the earthquake catalogues were obtained from different worldwide seismological network data. The earthquake catalogues obtained in different magnitude scale was converted into moment magnitude using regression analysis. The homogenized catalogue was then further subdivided into shallow crustal and deep subduction zone earthquake events for which, the seismic source parameters were obtained using Bounded Gutenberg-Richter Recurrence law. The seismic hazard maps were prepared in term of PGA at bedrock using the different ground motion attenuation relationships. The study shows that; the selection of appropriate ground motion prediction equation is an important factor in deciding the seismic hazard of Peshawar District. The inclusion of deep subduction earthquake does not add significantly to the seismic hazard. The calculated seismic hazard map for shallow crustal earthquake after including the epistemic uncertainty was in close agreement to that developed by BCP-2007 for a return period of 475 years on bedrock. The seismic hazard maps for other return periods i.e., 50, 100, 250 475, and 2500 years were then prepared.

Keywords: Seismic hazard map, Probabilistic seismic hazard analysis, BCP-2007, Peshawar

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1. Introduction:

Peshawar is the capital city of the Khyber Pakhtunkhwa province of Pakistan that has historical background in the history of indo-subcontinent. The city provides key access to the Central Asian States through Afghanistan along the Western borders of Pakistan. It is located at 710, 43.4' N latitude and 330, 93.7' E Longitude in the western Himalayan region.

Peshawar is characterized by high seismicity rates due to its vicinity to the active plate boundary between the Indian and Eurasian plates which are converging at rates of 37-42 mm/year (Chen et al., 2000). The Main Boundary Thrust (MBT) system along which the devastating Kashmir earthquake occurred in 2005 is located in the northern parts of the country together with some other active regional fault systems, which include Main Mantle Thrust (MMT) and Main Karakorum Thrust (MKT). These faults, if reactivated can act as a potential source of seismic hazard for the region including Peshawar (Waseem et al., 2013).

In term of seismic hazard previously the Building Code of Pakistan in 1986 has placed Peshawar in Zone 2 that corresponds to intensity V-VI on the Modified Mercalli Intensity scale. In the probabilistic study of MonaLisa et al. (2007) for the NW Himalayan thrust a value of 0.15g for PGA has been assigned to Peshawar. The seismic hazard study of Hashash et al. (2012) using discrete fault in Northern Pakistan suggest this PGA value in the range of 0.20-0.4g. Rafi et al. (2012) in the probabilistic seismic hazard analysis and zonation for Pakistan and Azad Jammu and Kashmir has evaluated a value of 0.175g for Peshawar Zone. Several researchers either regionally or partially has studied the seismic hazard of Peshawar District and has assigned different PGA value or in some range. Among them the Geological Survey of Pakistan (2006) Seismic Zoning Map suggests a PGA value in the range of 0.03-0.1g, Saeed and Warnitchai (2010) in the range of 0.33-0.4g and Zhang et al. (1999) in the range of 0.166-0.244g. These all previous studies using either deterministic or either probabilistic approach and different ground motion attenuation relationships have produced different level of seismic hazard for Peshawar in term of PGA value.

The Building Code of Pakistan, Seismic Provision 2007 (BCP-Seismic Provision, 2007) has defined Peshawar in Zone 2B. The Zone 2B has Peak Ground Acceleration (PGA) in the range of 0.16g to 0.24g for a return period of 475 years. The present study aims to calculate the seismic hazard of Peshawar and compare the same with that recommended by BCP-Seismic Provision, (2007). The PGA value at rock surface is calculated using the probabilistic seismic hazard analysis. The area source polygon as suggested by BCP-Seismic Provision 2007 are used as seismic sources for which the earthquake catalogues are obtained from worldwide seismogram network. The Modified Gutenberg Richter

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empirical model is used to calculate the seismic zone parameters for both shallow crustal and deep subduction zone earthquake. The seismic hazard in term of PGA at bedrock is then finally calculated and plotted in GIS environment. The different ground motion attenuation relationships compatible to the geology and seismicity of local environment are used to quantify the difference in seismic hazard results. Furthermore, the logic tree approach is used to lessen the epistemic uncertainty. The GIS based seismic hazard map developed for a return period of 475 years after including the epistemic uncertainty is then compared with the seismic hazard map suggested by (BCP-Seismic Provision, 2007). The seismic hazard maps are then further prepared for other return periods, i.e.,25, 50, 100, 250 and 2500 years.

2. Probabilistic Seismic Hazard Analysis

The uncertainties in the location, size and rate of recurrence of earthquake along with the variation in the ground motion in term of size and location can be well considered in the probabilistic seismic hazard analysis. The Probabilistic seismic hazard analysis (PSHA) provides a framework in which these uncertainties can be identified, quantified, and combined in a rational manner to provide a more complete picture of the seismic hazard (Kramer., 1996).

According to modified Gutenberg Richter Law the earthquake exceedance rate $\lambda(M)$ for an earthquake magnitude $\boldsymbol{M}$ can be defined as follow;

$$\boldsymbol{\lambda(M) = \lambda_o \frac{e^{-\beta M} - e^{-\beta M_u}}{e^{-\beta M_0} - e^{-\beta M_u}} , M_o \leq M \leq M_u} \qquad (\mathbf{1}),$$

λ_0 is the exceedance rate in the range of lower $\boldsymbol{M_o}$ and upper limit $\boldsymbol{M_u}$ of magnitude. β is earthquake source parameter

For the Poisson process, the probability density of the earthquake magnitude is given by

$$P(M) = \lambda_o \beta \frac{e^{-\beta M}}{e^{-\beta M_o} - e^{-\beta M_u}} \qquad (2)$$

Site specific seismic hazard analysis needed to estimate the strong ground motion from earthquake. The strong motion parameters such as acceleration and velocity are described in term of attenuation relationships that shows the decreases in strong motion with increasing distance from earthquake source. These attenuation relationships are developed for different regions depended on earthquake magnitude, source to site distance, site condition and tectonic environment using data from strong motion arrays. The general attenuation relationship for the peak horizontal acceleration has been developed by Campbell (1981) within 50 kM of fault rupture in magnitude 5.0 to 7.7 earthquake. Campbell and Bozorgnia (1994) developed attenuation relationships using worldwide moment magnitude in the range of 4.7 to 8.1. This relationship is more specific and provides additional terms for source characterization. Toro et al., (1994) has developed attenuation relation in term of peak horizontal acceleration on rock side for the continental portion of Northern America. Among other Boore and Atkinson., (2008) and Akkar and Bommer., (2010) developed site specific attenuation relationship that can calculate peak acceleration in term of earthquake magnitude, source to site distance, fault mechanism and site condition. The Boore and Atkinson., (2008) is derived from the empirical regression of PEER NGA strong-motion database while that of Akkar and Bommer, (2010) has been developed for Europe, Mediterranean. and Middle east.

The attenuation relationships already discussed can be used in shallow crustal earthquake. However, several researchers including Crouse et al., 1988; Crouse, 1991; Molas and Yamazaki, 1993; Youngs et al., 1995 have pointed out different conditions of attenuation relationships for shallow and subduction zones. Lin and Lee., (2008) and Kanno et al., (2006) developed attenuation relationship for earthquake records of Taiwan and Japan respectively. The study of Lin and Lee., (2008) showed lower attenuation for subduction zones than that for crustal shallow earthquake. The use of shallow crustal earthquake attenuation relationship may thus lead underestimate the seismic hazard in probabilistic analysis.

In probabilistic seismic hazard analysis, the peak acceleration at a location is a function of magnitude and distance that is lognormally distributed with standard deviation. In the hazard analysis, the study area is first divided into seismic sources based on geotechnical characterization. The different seismic sources are assumed to occur independently. All the points in a seismic source may be earthquake focus. The acceleration exceedance rates $v_i(a)$ for the single seismic source the i-th is calculated as:

$$v_i(a) = \sum_i w_{ij} \int_{M_o}^{M_u} \left(-\frac{d\lambda_i\,(M)}{dM}\right) Pr\left(A > a|M, R_{ij}\right) dM \qquad (3)$$

Where M_0 is the smallest and M_u is the largest magnitude of seismic source, $Pr(A>a|M,R_{ij}))$ is the probability that acceleration A exceeds the value a at distance R_{ij} for an earthquake of magnitude M. The acceleration exceedance $v(a)$ due to all sources-N of seismic zone is then calculated as:

$$v(a) = \sum_{i=1}^{N} v_i(a) \qquad (4)$$

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The magnitude exceedance rates, λ(M) is calculated from the earthquake catalogues using statistical analysis.

3. Seismicity of Peshawar

The collision of Eurasian and Indian plate has resulted in the formation of active Himalayan orogenic system that is further classified into Tethyan, Higher, Sub and Lesser Himalayas (Gansser, 1964). The divisions are based on the tectonic blocks formed and separated by major faults boundary.

The Microsoft Encarta Reference Library (2003) shows that the valley of Peshawar, consists of southern part of Eurasian plate and northern part of Indo-Australian plate. This part of the Himalayas is variably interpreted to be Lesser Himalayas (Tahirkheli et al., 1982) and Tethyan Himalayas (DiPietro and Pogue 2004). The deterministic study of Waseem et al., (2006) has identified about twenty-one seismogenic faults around Peshawar. Most of these faults have reverse faulting mechanism and have a Joyner and Boore distance R_{JB} in the range of 19-100kM. According to Ali and Khan., (2004), most of the earthquake felt at Peshawar have their origin in the Hindu Kush region of Afghanistan or Northern areas of Pakistan.

4. Example Problem

The seismic hazard software CRISIS-2007 was used to calculate the peak acceleration at bed rock for Peshawar District as shown in **Fig. 1**. The hazard analysis need seismic source geometry, earthquake reoccurrence relationship and the selected ground motion attenuation relationship. In the present study the ground motion attenuation relationships of Boore and Atkinson., (2008) and Akkar and Boomer., (2010) was used for shallow crustal seismic earthquakes and that of Lin and Lee., (2008) and Kanno et al., (2006) for deep subduction zone earthquake. The seismic hazard map was then further calculated in GIS environment with a grid size of 0.01 for various return period of 50, 100, 250, 475 and 2500 years.

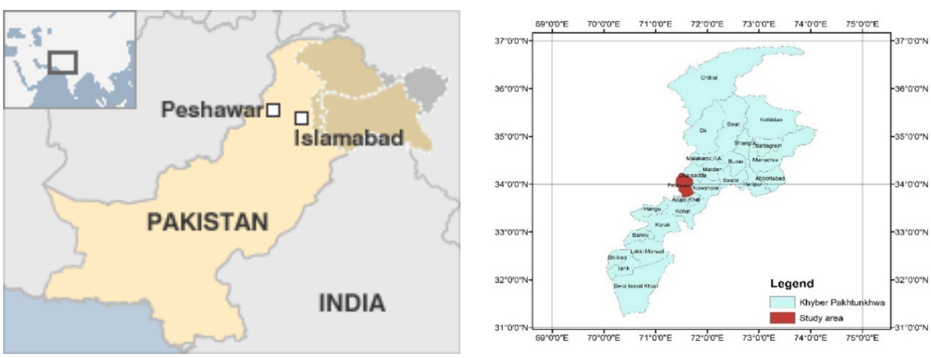

Figure. 1 Location of study area

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4.1 Seismic Sources Identification and Characterization

The building Code of Pakistan Seismic Provision, (BCP-2007) has defined the potential shallow seismic sources for Peshawar and are shown in **Fig. 2**.

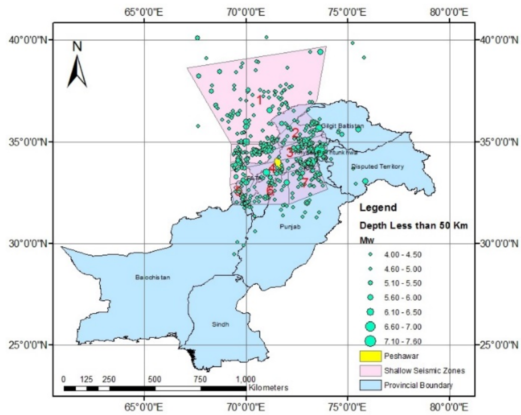

Figure. 2 Shallow seismic sources for Peshawar (BCP-2007)

The potential seismic sources for Peshawar region in a rectangular shape with latitude (31.888~ 36.006) and longitude (69.562~73.620) as shown in **Fig. 3** were considered for the probabilistic seismic hazard analysis. The earthquake catalogues were obtained using worldwide seismogram network sources i.e., United States of Geological Survey, (USGS), National Geophysical Data Center (NGDC), Global Centroid Moment Tensor (GCMT) and International Seismological Center (ISC) using the time span of 1500 AD till date with focal depth up to 1000m.

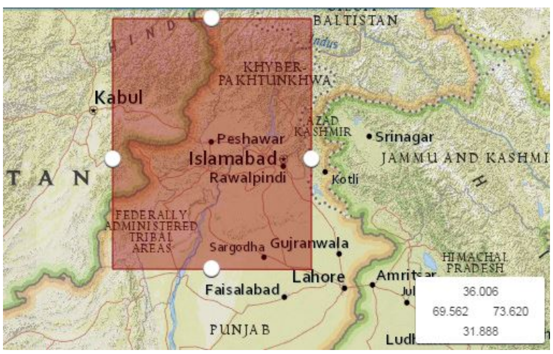

Figure. 3 Seismic source identification with defined latitude and longitude

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These different sources already discussed gives earthquake intensity in different types of magnitude i.e., Moment magnitude, Surface magnitude and Low magnitude. According to Kanamori, (1977) and Hanks and Kanamori, (1979) the moment magnitude is the most accurate scale that does not saturate in higher magnitude events. Therefore, all the magnitudes are converted into moment magnitude, (**Mw**) using regression analysis. **Figure. 5** shows the empirical relationships from regression analysis.

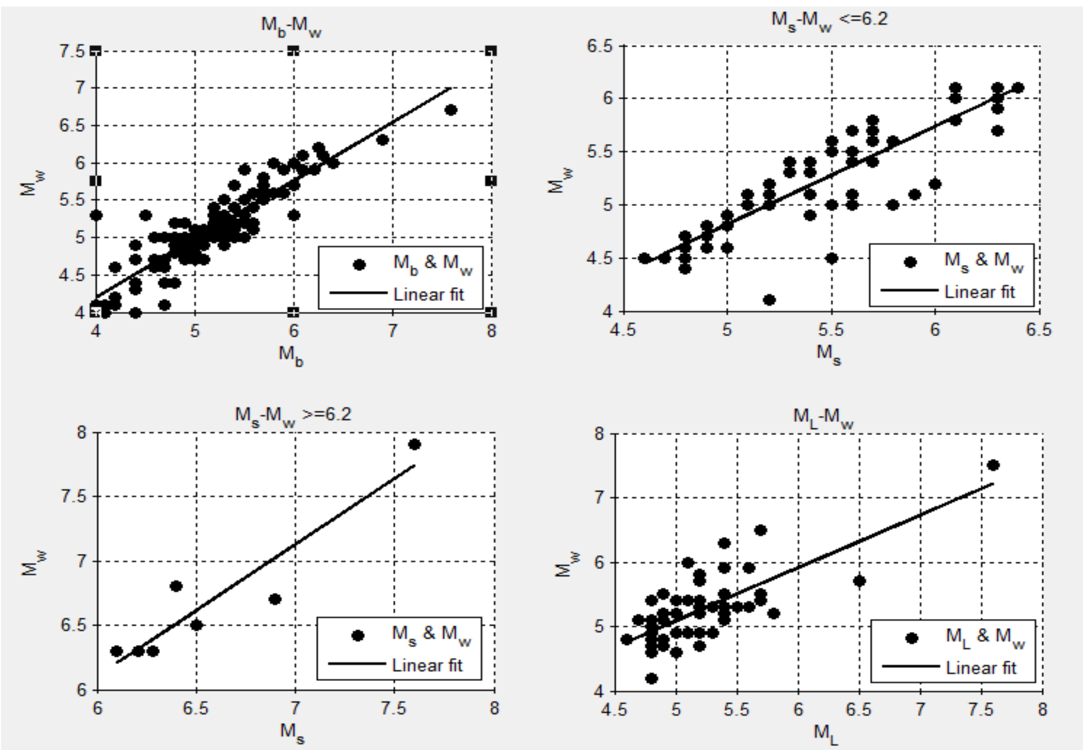

Figure. 4 Empirical relationships for Moment magnitude

The moment magnitude catalogue was further subdivided into shallow (depth less than 50 kM) and deep (depth more than 50 kM) earthquake events. **Figure. 5** shows the shallow and deep earthquake records along with seismic zones as defined in BCP-Seismic Provision, (2007). Furthermore, **Table. 1** shows the number of earthquakes along with maximum and minimum magnitude of each source.

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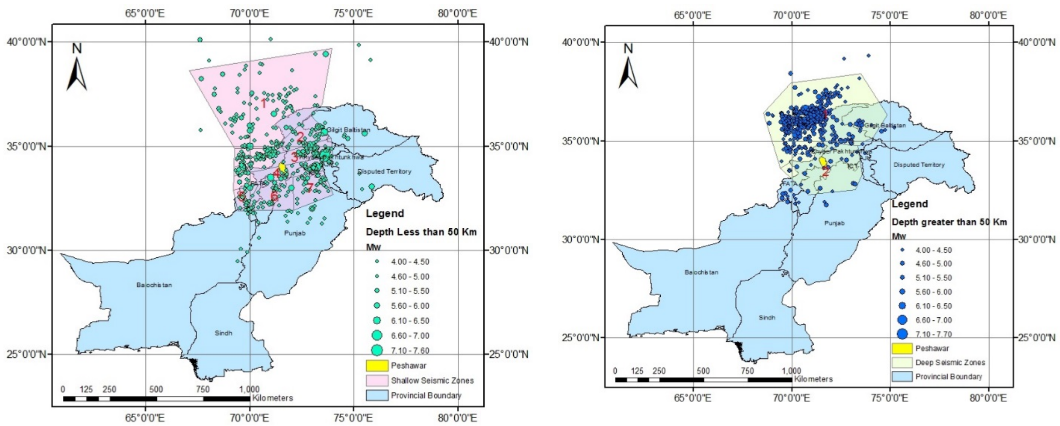

(a) Shallow crustal earthquake (b) Deep subduction zone earthquake

Figure. 5 Earthquake records from homogenized catalogue and with defined seismic sources

Table. 1: No. of earthquakes, minimum and maximum magnitude in shallow and deep seismic source

Zones	**1**		**2**		**3**	**4**	**5**	**6**	**7**
Depth, (kM)	<50	>50	<50	>50	<50	<50	<50	<50	<50
No. of Earthquakes	99	454	79	23	76	43	17	35	32
Minimum (Mw)	4.0	4.0	4.1	4.2	7.6	4.0	4.1	4.1	4.1
Maximum (Mw)	6.2	7.7	4.0	5.1	7.5	6.8	6.0	6.0	5.5

4.2 Seismic Source Parameters

The modified Gutenberg Richter reoccurrence law as given in **Eq. 1** is used in the present seismic hazard analysis. The seismic source parameters (i.e., η_o, β) are calculated from the graph $log_{\lambda_m} \sim M_w$ as shown in **Fig. 6** for both shallow and deep earthquakes in seven different zones as specified by building code of Pakistan, Seismic Provision, (2007).

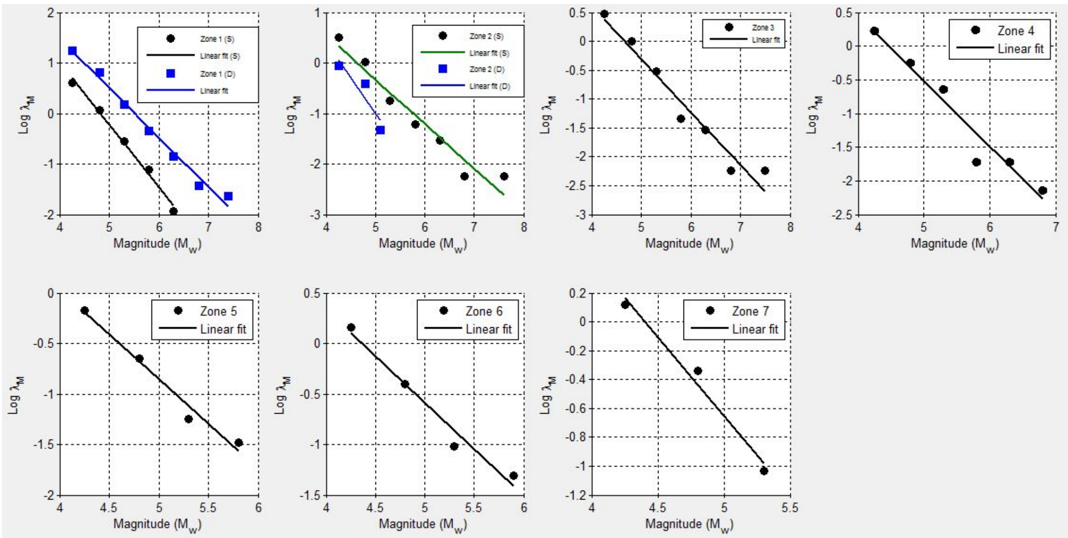

Figure. 6 The graph $log_{\lambda_m} \sim M_w$ for seismic source parameters of seven zones

Table. 2 Seismic source parameters for shallow and deep sources

Seismic Source	1	2	3	4	5	6	7	1*	2*
λ_o	10.055	3.625	4.075	2.876	1.059	2.143	2.731	24.143	5.652
$\beta = 2.303b$	2.832	2.03	2.10	2.24	2.03	2.10	2.5	2.17	2.97
M_u	6.2	7.6	7.5	6.8	6.0	6.0	5.5	7.7	6.0

1,2,3,4,5,6 and 7 are shallow seismic sources and 1*, 2* are deep seismic sources

4.3 Attenuation Relationship and Peak Ground Acceleration

The attenuation relationships were used to predict the ground shaking level i.e., Peak Ground Acceleration (PGA), Peak Ground Velocity and Spectral Acceleration (SA) at different frequency for the site of interest. The attenuation relationships for a site are developed using substantial dataset information (Cotton et al. ,2006). The attenuation relationships are not available for Pakistan because of the very scarcity of available strong motion data. The alternate to this is to use the already available attenuation relationships of other regions having similar tectonic and geological conditions to Pakistan. In case of shallow earthquake, the candidate attenuation relationships for north Pakistan should be the one developed for the active tectonic crustal earthquake region. In the present study the ground motion attenuation relationship of Akkar and Boomer, 2010, and Bore and Atkinson, NGA 2008 were used to calculate the Peak Ground Acceleration, (PGA) for shallow earthquake. Furthermore, the ground motion

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attenuation relationships of Lin and Lee., (2008) and Kanno et al., (2006) developed for subduction zones are used for deep earthquake. The seismic hazard in term of PGA was then calculated at bedrock site for different return periods 50, 100, 250, 475 and 2500 years and were plotted in Geographical Information System (GIS) environment to obtain the seismic hazard maps for these different ground motion attenuation relationships.

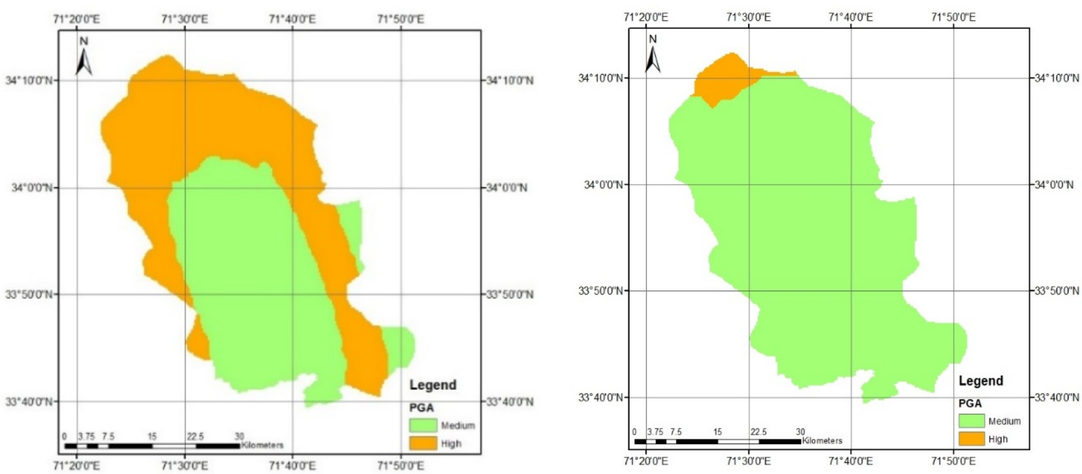
4.4 Seismic Hazard Maps

The seismic hazard level based on peak acceleration, (g) at bedrock are given in **Table. 3**.

Table. 3 Seismic hazard level used in GIS

Seismic Hazard Level	Peak acceleration, (g)
Very low	< 0.08 g
Low	0.08 - 0.16 g
Medium	0.16 - 0.24
High	0.24 - 0.32
Very high	> 0.32 g

The seismic hazard maps for a return period of 475 years in case of shallow crustal earthquake and deep earthquake for Peshawar District are shown in **Fig. 7** and **8** respectively.



(a) Akkar and Boomer (2010) (b) Boore and Atkinson, NGA (2008)

Figure. 7 Seismic hazard maps for shallow crustal earthquake using different attenuation equations

Figure. 7 shows that for a return period of 475 years, the predictive relationship of Akkar and Boomer, (2010) overestimates the PGA value in comparison to that of Boore and Atkinson (2008). According to Arango et al. (2012), the distance scaling factor of the later appears to be more adequate then the

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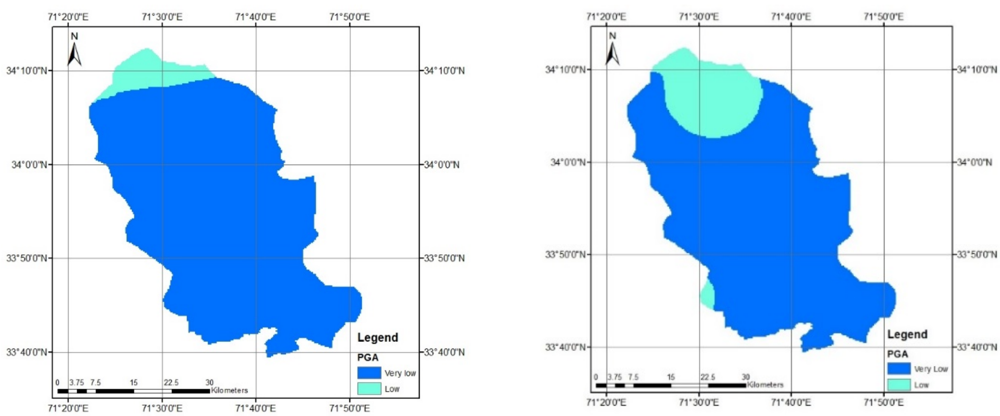
previous. Furthermore, **Table. 5** shows a slight comparison of both ground motion prediction equations that suggests that in term N_R=Number of records, T_{max}= longest response period, M_w = moment magnitude and [R] = distance range, the prediction equation of Boore and Atkinson (2008) is more appropriate and reliable than that of Akkar and Boomer (2010).

Table. 4 Comparison of predictive equations used for shallow crustal earthquake (after, Arango, et al., 2012)

Predictive equation	**Tectonic Regime**	**Region**	N_R	T_{max}	M_w	**[R]**
Boore and Atkinson (2008)	Shallow crustal	Worldwide	1574	10	5-8	0-200
Akkar and Boomer (2010)	Shallow crustal	Europe/Middle east	532	3	5-7.6	0-100

Figure. 8 shows, the seismic hazard maps for deep subduction earthquake using Lin and Lee (2008) and Kanno et al. (2006) for a return period of 475 years. According to this **Fig. 8** both the attenuation equations resulted somewhat same seismic hazard for Peshawar District. Furthermore, it is also clear from the **Fig. 8** that, the inclusion of deep subduction zones in the seismic hazard does not contribute significantly i.e., it remains low (0.08-0.16g) to very low (<0.08g).



(a) Lin and Lee (2008)

(b) Kanno et al. (2006)

Figure. 8 Seismic hazard maps for deep subduction earthquake using different attenuation equations and for a return period of 475 years

In probabilistic seismic hazard analysis (PSHA), one of the major sources of uncertainty is the epistemic uncertainty i.e., appropriate selection of predictive relationship. The different ground motion attenuation relationships already discussed are further used to find out the epistemic uncertainty in the seismic hazard

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analysis. The logic tree approach is therefore used in which weighting factor is assigned to alternate attenuation model (**Fig. 9**).

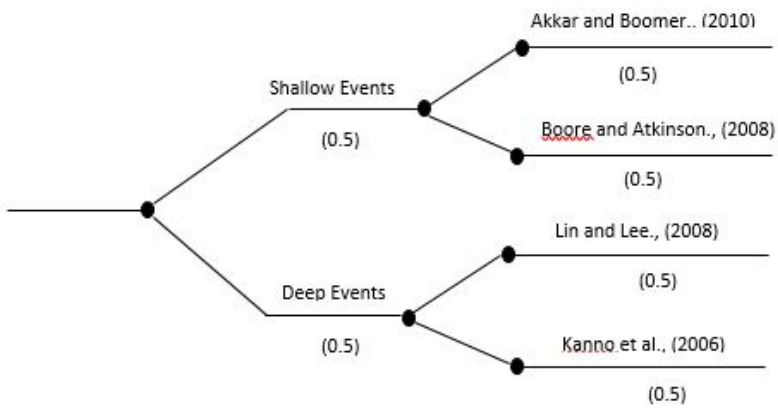
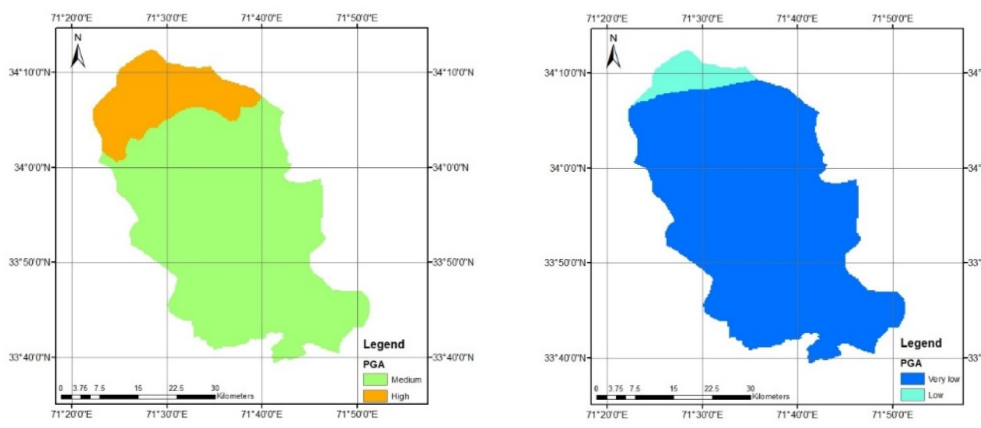


Figure. 9 Logic Tree for incorporating epistemic uncertainty

Figure. 10 shows the seismic hazard maps for shallow and deep events after incorporating the epistemic uncertainty. As can be seen in **Fig. 10a**, the seismic hazard of Peshawar District becomes balanced in between the seismic hazard predicted by Akkar and Boomer (2010) and that of Boore and Atkinson (2008). The reason is that of providing equal weightage to both the predictive relationship in hazard analysis. The seismic hazard in case of deep subduction zone earthquake remains somewhat same after incorporating epistemic uncertainty (**Fig. 10b**). It can also be further concluded that the earthquake produced by deep subduction zone are not so sever in term of seismic hazard. Thus, it means that, the shallow crustal earthquake significantly adds to the seismic hazard.



(a) Shallow crustal earthquake (b) Deep subduction zone earthquake

Figure. 10 Seismic hazard maps after incorporating epistemic uncertainty for 475 years return period

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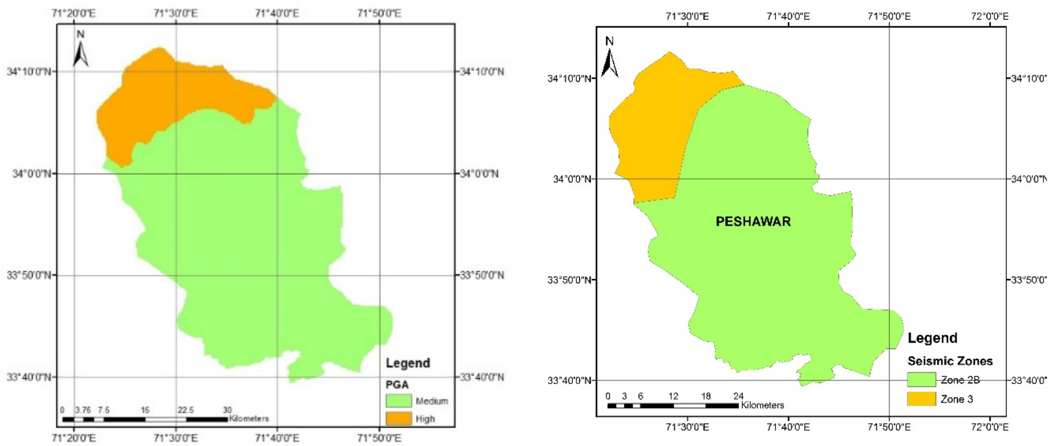
The calculated seismic hazard map after incorporating epistemic uncertainty is compared with the hazard map from the BCP-2007. For the return period of 475 years, a close agreement between the two seismic hazard maps can be noticed (**Fig. 11**). After this check the seismic hazard maps for other return periods i.e., 25, 50, 100, 250 and 2500 years were prepared.



(a) Calculated with epistemic uncertainty (b) BCP (2007)

Figure. 11 Comparison of seismic hazard maps for a return period of 475 years

5. Discussion and Conclusions

The selection of appropriate ground motion prediction equation is an important factor in deciding the seismic hazard of Peshawar District. In case of shallow crustal earthquake, the predictive relationship of Akkar and Boomer, (2010) provide higher estimate of the PGA value in comparison to that of Boore and Atkinson (2008). The distance scaling factor of the later appears to be the reason for this disparity among the two models.

The inclusion of deep subduction earthquake does not add significantly to hazard and may be neglected in term of seismic hazard. Therefore, these are only the shallow crustal earthquake that decides the seismic hazard of Peshawar District. However, recent earthquakes in Peshawar from deep sources earthquakes has caused widespread destruction in various parts of the district. This raise concern for the existing GMPEs and the classical PSHA procedure to simulate such effects.

The epistemic uncertainty was used by providing equal weightage to the attenuation equation of Akkar and Boomer (2010) and that of Boore and Atkinson (2008). The calculated seismic hazard map thus produced was balanced by that developed using these attenuation relationships. Furthermore, there was also a close agreement between the calculated seismic hazard and that developed by BCP-2007 for a return period of 475 years on bedrock. However, the BCP places Peshawar in Zone 2B, which is reasonable for most of the locations but it underestimates ground motions especially in northern parts of the city.

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References

Ali, Q., Khan, A.N.: A critical review of the seismic hazard zoning of Peshawar and Adjoining areas. Journal of Earthquake Engineering, 9, 587-607.

Akkar, S., Bommer, J.J.: Empirical Equations for the Prediction of PGA, PGV, and Spectral Accelerations in Europe, the Mediterranean Region, and the Middle East. Seismological Research Letters, 81, 2010.

Arango, M.C., Free, M.W., Lubkowski, Z.A., Pappin, J.W., Musson, R.M.W., Jones, G., Hodge, E.: Comparing predicted and observed ground motions from UK earthquakes. Proceeding of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 2012.

BCP: BCP-SP - Building Code of Pakistan Seismic Provision. Ministry of Housing and Works, Islamabad, 2007.

Boore, D.M., Atkinson, G.M.: 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, 24, 99-138, 2008.

Campbell, K.W., Bozorgnia., Y.: Empirical analysis of strong ground motion from the 1992 Landers, California, earthquake. Bulletin of the Seismological Society of America, 84, 573-588, 1994.

Chen, Z., Burchfiel, B.C., Liu, Y., King, R.W., Royden, L.H., Tang, W., Wang, E., Zhao, J., Zhang, W.: GPS measurement from eastern Tibet and their implications for India/Eurasia intercontinental deformation. Journal of Geophysical Research, 105, 16-215, 2000.

Cotton, F., Scherbaum, F., Bommer, J.J., Bungum, H.: Criteria for selecting and adjusting ground-motion models for specific target regions: application to central Europe and rock sites. Journal of Seismology, 10, 137-156, 2006.

CRISIS: User Manual Crisis 2007 Version 7.2. In: Ordaz, M., Aguilar, A., Arbulida, J. (Eds.). A computer program for seismic hazard assessment. Institute of Ingeneria, UNAM, 2007.

Campbell, K.W.: Near source attenuation of peak horizontal acceleration. Bulletin of the Seismological Society of America, 71, 2039-2070, 1981.

Crouse, C.B.: Ground-motion attenuation equations for earthquakes on the Cascadia subduction zone. Earthquake Spectra, 7, 210-236, 1991.

Crouse, C.B., Vyas, Y.K., Schell, B.A.: Ground motions from subduction-zone earthquakes. Bulletin of the Seismological Society of America, 78, 1- 25, 1988.

https://doi.org/10.5194/nhess-2019-299
Preprint. Discussion started: 26 November 2019

DiPietro, J.A., Pogue, K.R.: Tectonostratigraphic subdivisions of the Himalaya: A view from the west. Tectonics, 23, 1-20, 2004.

Gansser, A.: Geology of the Himalayas. Inter-Science Publication. Jon Wiley and Sons, London, 1964.

Hanks, T. C., Kanamori, H.: A moment magnitude scale. Journal of Geophysical Research, 84, 2348 - 2350, 9B0059, doi:10.1029/JB084iB05p02348, 1979.

Hashash, Y.M, Kim, B., Olson, S.M., and Ahmad, I.: Seismic hazard analysis using discrete faults in Northwestern Pakistan: Part I-methodology and evaluation. Journal of Earthquake Engineering, 16, 963-964, 2012.

Kanamori, H.: The energy release in great earthquakes. Journal of Geophysical Research, 82, 298 I-2987, 1977.

Kanno, T., Narita, A., Morikawa, N., Fujiwara, H., Fukushima, Y.: A new attenuation relation for strong ground motion in Japan based on recorded data. Bulletin of the Seismological Society of America, 96, 879-897, 2006.

Kramer, L.K.: Geotechnical Earthquake Engineering. Prentice-Hall, New Jersy, USA, 1996.

Lin, P-S., Lee, C.T.: Ground-Motion Attenuation Relationships for Subduction Zone Earthquakes in Northeastern Taiwan. Bulleting of the Seismological Society, 98, 220-240, 2008.

Molas, G.L., Yamazaki, E.: Attenuation of earthquake ground motions in Japan including deep focus events. Bulletin of the Seismological Society of America, 85, 1343-1358, 1995.

MonaLisa, Khawaja, A.A., Jan, M. Q.: Seismic hazard assessment of NW Himalayan thrust belt using probabilistic approach. Journal of Earthquake Engineering, 11, 257-301, 2007.

Rafi, Z., Lindholm, C., Bungum, H., and Ahmed, N.: Probabilistic seismic hazard analysis and zonation of Pakistan, Azad Jammu and Kashmir. Natural Hazards, 61, 1317-1354, 2012.

Zaman, S., and Warnitchai, P.: Probabilistic seismic hazard maps for Pakistan. In Proceedings of the 15th World Conference on Earthquake Engineering, Bangkok, Thailand, 2010.

Tahirkheli, R.A.: Geology of the Himalayas, Karakorum, and Hindu Kush in Pakistan. University of Peshawar Geological Bulletin, 15, 1-49, 1982.

Toro, G.R., Abrahamson, N.A. and Schneider, J.F.: Model of strong ground motions from earthquakes in Central and Eastern North America: best estimates and uncertainties. Seismological Research Letters, 68, 41-57, 1997.

Toro, G.R., Abrahamson, N.A., and Schneider, J.F., 1995. Engineering model of strong ground motions from earthquake in the central and eastern United States, Earthquake Spectra, in press.

Waseem, M., Khan., M.A., Javed., M. W., Ali., S.M.: Deterministic seismic hazard analysis for Peshawar, Pakistan. Journal of Himalayan Earth Sciences, 46, 67-72, 2013.

Youngs, R.R., Abrahamson, N.A., Makdisi, E., Sadlgh, K.: Magnitude dependent dispersion in peak ground acceleration. Bulletin of the Seismological Society of America, 85, 1161-1176, 1995.

Youngs, T.LR., Chiou, S.J., Silva, W.L., Humphrey, J.R.: Strong ground motion attenuation relationships for subduction zone earthquakes based on empirical data and numerical modeling (abs.), Seismological Research Letters, 64, 58-73, 1993.

Zhang, P. Z., Yang, Z-X, Gupta, H.K., Bhatia, S.C., Shedlock, K.M.: Global seismic hazard assessment program (GSHAP) in continent Asia; Annali di geofisica, 42, 1167-1190, 1999.