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PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR ISLAMABAD AND PESHAWAR IN PAKISTAN USING DISCRETE FAULTS

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ABSTRACT

Northwestern Pakistan is located at the western edge of the Himalayas and is criss-crossed by numerous active faults such as the Main Boundary Thrust (MBT) and the Main Mantle Thrust (MMT). As a result, northwestern Pakistan has experienced numerous destructive earthquakes in its history. However, previously published seismic hazard studies for the region have yielded low bedrock peak ground acceleration (PGA) values. These low values are inconsistent with high accelerations observed during the 2005 Kashmir Earthquake. In this study, the authors propose revised seismic sources that reflect recent understanding of local seismicity and identified faults. The study uses an earthquake catalogue that includes historical as well as more recent instrumental seismicity that spans from the year 1505 to 2006, and characterizes 32 primary faults in the region using procedures defined by the U.S. Geological Survey for developing the U.S. National Seismic Hazard Maps. We performed probabilistic seismic hazard analyses (PSHA) using the commercially-available software "EZ-FRISK," focusing on two cities (Islamabad and Peshawar) that are proximate to major thrust faults. In the analyses, we employed four relationships from the Next Generation Attenuation of Ground Motions (NGA) Project to predict ground motions. The PGA for Islamabad is estimated at 0.39 g for a 475-yr return period, two to three times larger than previous estimates.

Keywords: probabilistic seismic hazard analysis, northwestern Pakistan, faults, ground motion attenuation.

INTRODUCTION

On 8 October 2005, a moment magnitude (M_W) 7.6 earthquake with a focal depth of 26 km occurred in northwestern Pakistan (34.493˚N, 73.629˚E), followed by numerous aftershocks (USGS 2010). The main shock and aftershocks caused at least 86,000 fatalities and more than 69,000 injuries (USGS 2010). This earthquake was also responsible for geotechnical failures including extensive landsliding and liquefaction, in addition to thousands of building collapses (Aydan et al. 2009; Bhat et al. 2005; Jayangondaperumal et al. 2008). The earthquake triggered over 2,400 landslides that destroyed housing and buried mountain roads and highways (Sato et al. 2007). This earthquake renewed international attention on the importance of seismic hazards in Pakistan.

Since 2005, several seismic hazard studies have been conducted in Pakistan. These studies include developing historical earthquake databases and performing seismic hazard analyses for various portions of the country, including those by Monalisa et al. (2007), NORSAR and PMD (2006), and PMD and

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NORSAR (2006). However, these studies are hampered by source zone characterizations. This study provides estimates of probabilistic seismic hazard using updated assumptions of seismicity that incorporate individual faults in northwestern Pakistan.

TECTONIC SETTING

Pakistan is located in the collision zone between the Eurasian Plate and the Indian Plate, the latter of which translates northward at a rate of about 45 mm/year and rotates counterclockwise based on available GPS data (Sella et al. 2002). This collision has produced the Himalayan mountain ranges and flexures. The rotation and translation of the Indian Plate causes left-lateral slip of 42 mm/year in Baluchistan and right-lateral slip of 55 mm/year in the Indo-Burman ranges (Bilham 2004). Larson et al. (1999) reported the Himalayan convergence rate of 18 ± 2 mm/yr, consistent with the velocity difference between the Indian Plate (44 mm/yr) and the South Tibet region of the Eurasian Plate (29 mm/yr) as shown in Figure 1. Due to this plate movement, Pakistan has experienced large and destructive earthquakes throughout its history. The two main active fold-and-thrust belts in northwestern Pakistan region are the Sulaiman belt and the NW Himalayan belt as shown in Figure 1. The Sulaiman mountain belt at the northwestern margin of the Indian subcontinent is part of the Chaman Fault where the 2008 Balochistan earthquake (M_W = 6.4) occurred. This paper is focused on the NW Himalayan belt, which is associated with the Himalayan convergence (Jadoon et al. 1997) and includes several major thrust faults such as the Main Mantle Thrust (MMT) and Main Boundary Thrust (MBT).

PROBABILISTIC SEISMIC HAZARD ANALYSIS

Probabilistic seismic hazard analysis (PSHA, Cornell (1968)) provides a framework in which uncertainties in size, location, and rate of recurrence of earthquakes and in the variation of ground motion characteristics can be identified, quantified, and combined in a rational manner. PSHA is commonly divided into four steps. The first step is to identify and characterize earthquake sources. Probability distributions of potential rupture locations within the source are assigned to each source. The second step is to characterize earthquake recurrence for each source. In order to do this, a recurrence relationship, which specifies the average rate at which an earthquake of a given size will be exceeded, is used. The third step is to determine select ground motion parameters using appropriate predictive relationships. The final step is to evaluate the probability that the select ground motion parameter will be exceeded during a particular time period.

Source characterization

Thirty-two faults in NW Pakistan were characterized for this study based primarily on Monalisa et al. (2007). The Main Karakoram Thrust (MKT) was not considered in this seismic hazard study because it is located more than 200 km away from the major cities of Islamabad and Peshawar, and has little influence on seismic hazard in those cities. In some cases, faults in proximity to each other were considered as a single fault. Most of these faults are thrust or reverse faults. There are also several normal faults and strike-slip faults in the study area. However, detailed information about the geometry of faults is not yet available. In lieu of fault specific data, various depths were weighted and combined in a logic tree to represent uncertainty in fault geometries.

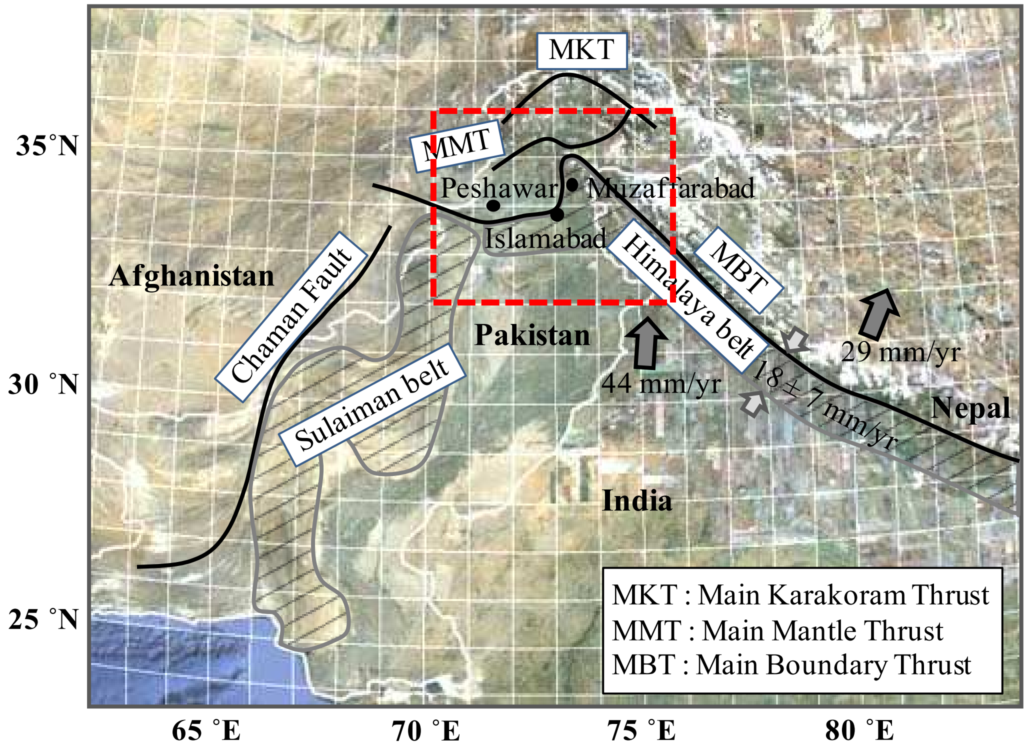


Figure 1. General tectonic setting of Pakistan with plate velocities from Larson et al. (1999). Major faults with two active belts are shown. Rectangle denotes the study area in NW Pakistan.

The Quaternary faults in NW Pakistan are considered to be similar to those in California, U.S. because they are similar in age and located along plate boundaries. The faults in California are relatively well-studied, therefore their geometry was incorporated into our interpretation of fault geometries in NW Pakistan. Some faults are exposed at the ground surface and can be readily traced; however, many blind faults also are present. The depth to the top of rupture, termed Z_{tor}, defines whether the fault is blind, and we assigned each fault the same values and weights for Z_{tor} as used by the USGS seismic hazard mapping project (Petersen et al. 2008). Specifically, we assigned Z_{tor} = 0, 2 km, and 4 km based on the maximum earthquake magnitude each fault is capable of producing. The depth to the bottom of rupture (D) was set equal to 10 km, 15 km, and 20 km with weights assigned based on the USGS databases from the Intermountain West, Pacific, and California faults. It is assumed that the thrust faults dip at 30° to the north or northeast, and the normal and reverse faults dip at 60° to the north or northeast.

Recurrence relationship

Earthquake catalogues from the USGS, BAAS (British Association for the Advancement of Science, Seismological Committee), ISS (International Seismological Summary, 1964~present), ISC (International Seismological Centre, 1918-1963), MSSP (Micro-seismic Studies Program), and PMD (Pakistan Meteorological Department) were combined to create a composite catalogue for Pakistan. Figure 2 presents the number of earthquakes with time in the catalogue. Different magnitude scales were converted to moment magnitude prior to use in the seismic hazard analysis. The earthquakes with great depth were excluded in the analysis unless the magnitude was sufficiently large to influence the seismic hazard. Specifically, we excluded earthquakes with focal depths > 35 km and M_W < 5 as well as those with focal depths > 45 km and M_W < 6.

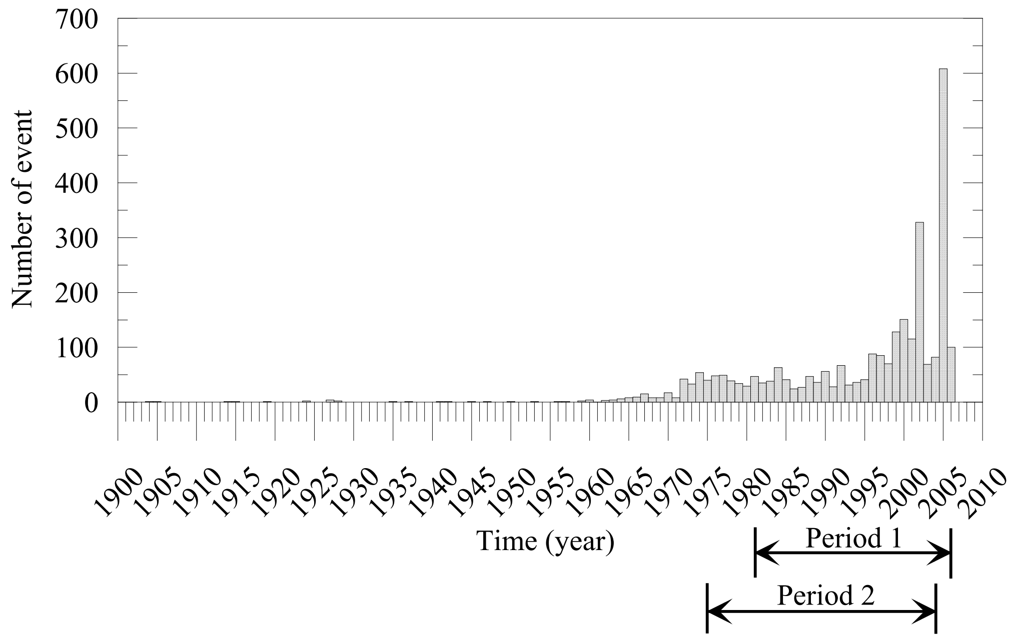


Figure 2. Number of earthquakes in a study area (32˚N-36˚N, 70˚E-76˚E). Earthquakes in two different periods were used in this study are shown: Period 1 (1981-2006) and Period 2 (1975-2004).

The truncated Gutenberg-Richter recurrence relationship was used in this study. The general form of the Gutenberg-Richter exponential recurrence relationship can be expressed as (Richter 1958):

$$\log N(m) = a - bm \tag{1}$$

where $N(m)$ is the cumulative number of earthquakes with M_W > m, and a and b are constants. The truncated Gutenberg-Richter recurrence relationship can be expressed as (Cornell and Van Marke 1969):

$$N(m) = N(m^0)\frac{\exp\left(-\beta(m-m^0)\right)-\exp\left(-\beta(m^u-m^0)\right)}{1-\exp\left(-\beta(m^u-m^0)\right)} \text{ for } m \le m^u \tag{2}$$

where m^0 is the threshold magnitude, m^u is the upper bound magnitude, and $\beta = 2.303 \cdot b$.

The activity rate for the truncated Gutenberg-Richter recurrence relationship was estimated by dividing the number of earthquakes above the threshold magnitude (m^0 = 4) that occurred in each seismic zone in each time period. The activity rates for each source zone corresponding to each time period (Period 1 and 2) were equally weighted for this study. Considering that the earthquake catalogue appears incomplete before 1970, Period 1 corresponds to 1981~2006 and Period 2 corresponds to 1975~2004, excluding 2005 in order to avoid bias from the aftershocks of the 2005 Kashmir earthquake.

The upper bound magnitude in Eq. (2) was estimated using magnitude-rupture area relationships proposed by Wells and Coppersmith (1994), Hanks and Bakun (2008), and Ellsworth-B (WGCEP 2003), as follows. A first upper bound magnitude was computed using the Wells and Coppersmith (1994) relation for rupture areas (RA) < 500 km^2 and the Ellsworth-B (WGCEP 2003) relation for RA ≥ 500 km^2. A second magnitude was computed using the Wells and Coppersmith (1994) relation for RA < 537 km^2 and the

Hanks and Bakun (2008) relation for RA≥ 537 km^2. These two upper bound magnitudes were averaged for use in the logic tree discussed later. Weights of 0.6, 0.2, and 0.2 were assigned to the mean upper bound magnitude, mean upper bound + 0.5 magnitude units, and mean upper bound – 0.5 magnitude units, respectively, assuming a normal distribution.

If fault slip is slow, no detectable energy is released. This is termed aseismic slip. WGCEP (2003) used a seismogenic scaling factor, R, to account for aseismic slip. If aseismic slip occurs, earthquake recurrence generally decreases. Thus by reducing the upper bound magnitude of the source in proportion to the aseismic rate, the effects of creep can be taken into account. By multiplying the known rupture area by R, the rupture area is reduced to the seismogenic area. This approach reduces the upper bound magnitude through its relationship with rupture area. In this project, we used R = 0.8, 0.9, and 1.0 with weights of 0.2, 0.6, and 0.2, respectively, for all NW Pakistan source zones. The weights assume analogies between Quaternary faults in California, U.S. and similar age faults in Pakistan.

The last parameter needed to develop the recurrence relationship is the b-value. It establishes the slope of exponential recurrence model and should be estimated using the earthquake distribution assigned to each source zone. However, incompleteness of combined earthquake catalogue complicates the determination of b-values. It is likely that the incomplete earthquake catalogue increases the slope of the recurrence plot, resulting in an underestimate of the seismic hazard. Petersen et al. (2008) used fixed b-values of 0.8 for all source zones in the USGS seismic hazard mapping project. Some source zones used in this study have b ~ 0.8, while others exhibit larger b-values, lowering the recurrence rate. To avoid underestimating the recurrence rate due to an incomplete earthquake catalogue, we assigned b = 0.8 for all NW Pakistan sources. Figure 3 presents the recurrence relationship for the MBT west section.

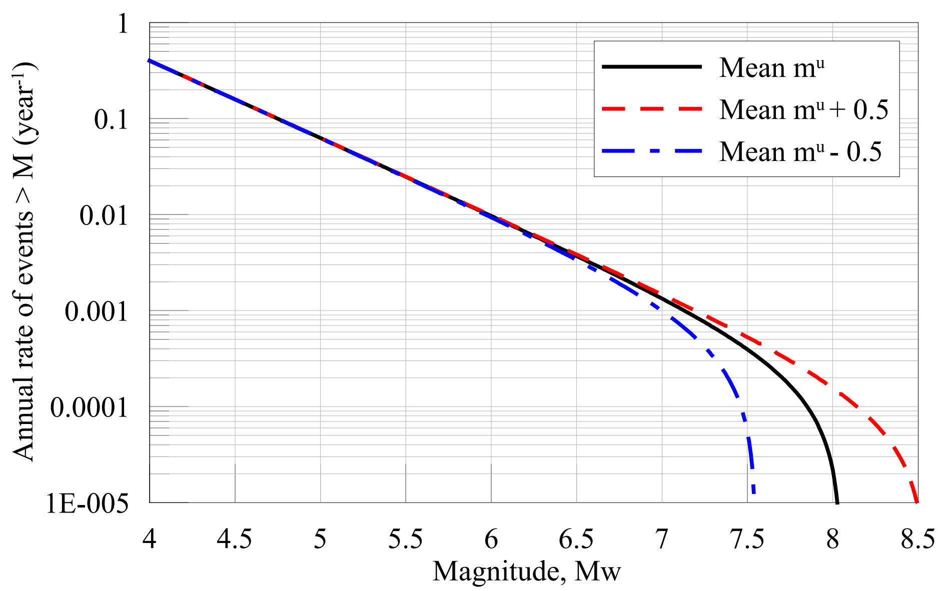
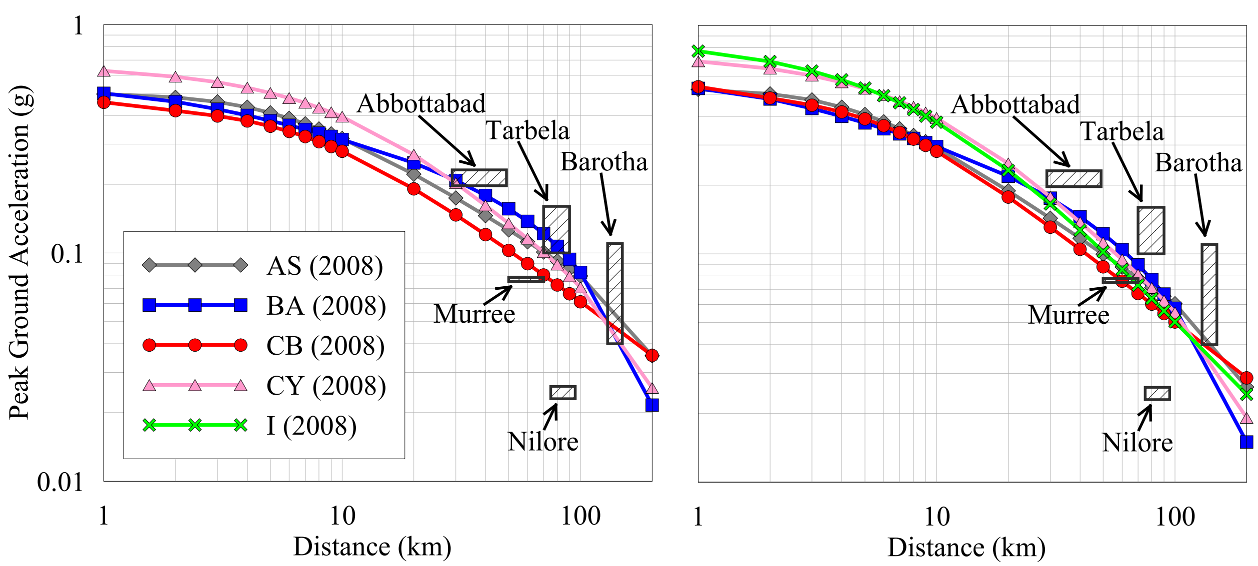


Figure 3. Recurrence model for MBT west section using mean upper bound magnitude (m^u) and mean m^u ± 0.5.

Attenuation relationships

The "Next Generation Attenuation (NGA) Models" for ground motion was a multidisciplinary research program coordinated by the Lifelines Program of the Pacific Earthquake Engineering Research (PEER) Center, in partnership with the USGS and the Southern California Earthquake Center (SCEC) to develop new ground-motion prediction relations (Power et al. 2008). NGA models are available for peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped elastic pseudo-response spectral accelerations in the period range of 0 to 10 seconds. Shallow crustal earthquakes with various fault mechanisms (strike-slip, normal, and reverse) can be used with the NGA models. Moment magnitude range and distance range of NGA models are 5 to 8.5 and 0 to 200 km, respectively. Five sets of NGAs were examined in this study: Abrahamson-Silva (AS) (2008), Boore-Atkinson (BA) (2008), Campbell-Bozorgnia (CB) (2008), Chiou-Youngs (CY) (2008), and Idriss (I) (2008).

To evaluate the applicability of the NGA relations to Pakistan, Figure 4 compares PGAs measured during the 2005 Kashmir earthquake (Durrani et al. 2005) with PGAs predicted by the NGAs. The measured data include a distance uncertainty of ± 10 km and illustrate the range of PGA in orthogonal horizontal directions and at different stations across a site. We used two site conditions to generate the PGA predictions: (1) soft soil with average shear wave velocity in the upper 30 m ($V_{s,30}$) of 270 m/s (NEHRP class D); and (2) stiff soil with $V_{s,30}$ = 560 m/s (NEHRP class C). Note that the Idriss (2008) relation does not apply to soft soils. The soft soil NGA predictions capture all recorded PGAs except the Nilore site. This PGA value was likely affected by the raft foundation dimensions where the instrument was placed (Durrani et al. 2005). Although the NGAs slightly underestimate recorded PGAs in Abbottabad, Tarbela, and Barotha, the overall agreement is reasonable.



(a) NGAs for soft soil ($V_{s,30}$ = 270 m/s) (b) NGAs for stiff soil ($V_{s,30}$ = 560 m/s)

Figure 4. PGA predictions by five NGAs compared with measured strong motions for the 2005 Kashmir earthquake.

Following current U.S. practice, we computed seismic hazard for uniform firm rock conditions corresponding to $V_{s,30}$ = 760 m/s (NEHRP B/C boundary). Figure 5 shows the PGAs predicted using the NGA relations for a M_W 8.0 event on a thrust fault with depth = 15 km and dip angle = 30˚. As expected, the predicted PGAs for the hanging wall side of the thrust fault exceed the foot wall values until the source-to-site distance exceeds the distance to the surface projection of the fault plane. This hanging wall effect is one of the new features in the NGA models. However the Chiou and Youngs (2008) relationship predicts significantly larger PGAs near the fault than the other NGAs. As a result, we excluded this relation and equally weighted the remaining four relations for use in the PSHA.

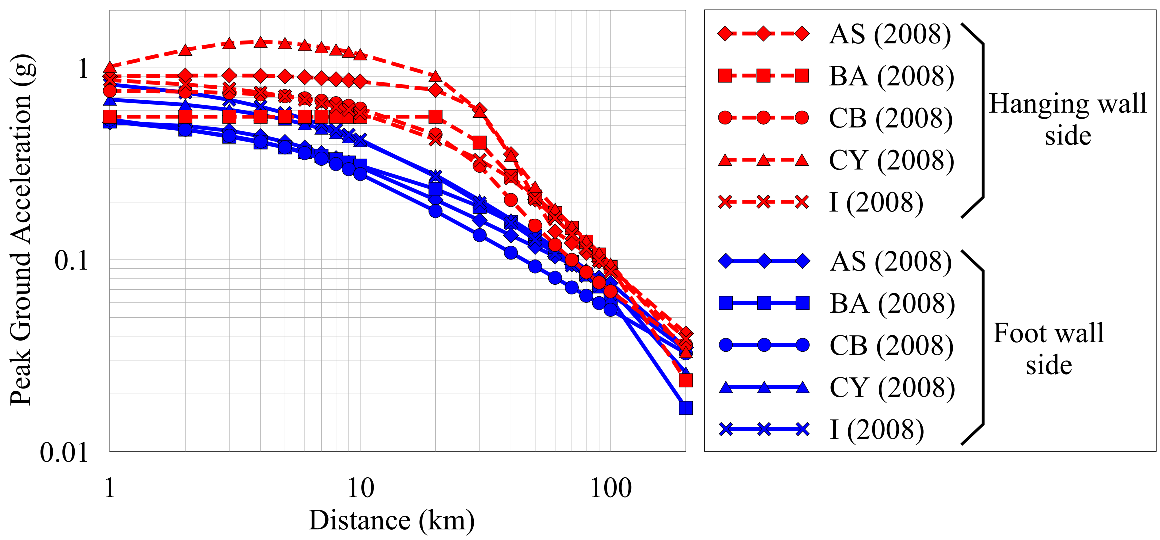
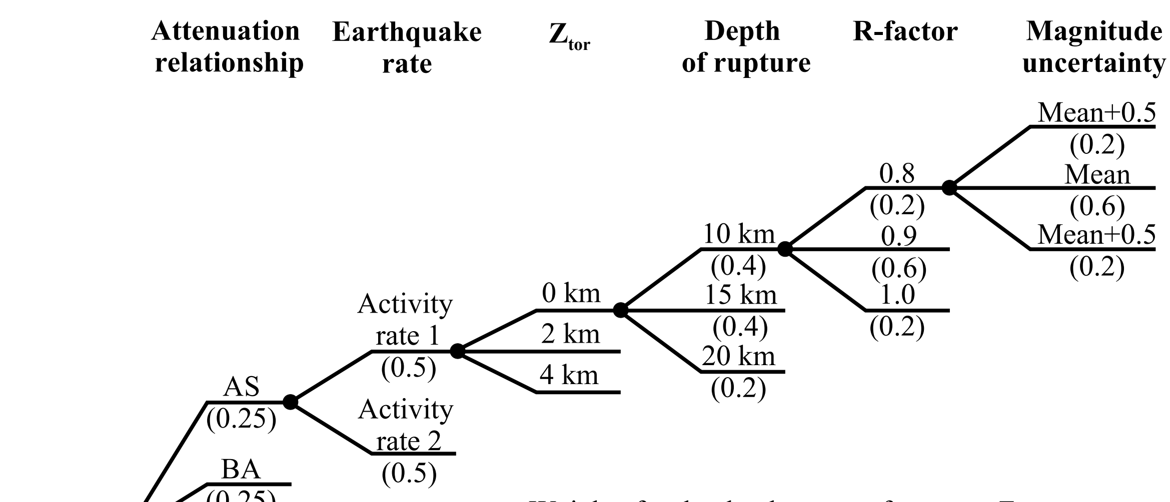


Figure 5 PGA values predicted by NGA attenuation relations for M_W 8.0 earthquake on a thrust fault with focal depth = 15 km, dip angle = 30˚, and $V_{S,30}$ = 760 m/s.

Logic tree

A PSHA inherently allows users to incorporate uncertainties related to fault geometries and earthquake recurrence rates (among others), which is especially important for regions like Pakistan where source characteristics are not well-established. All parameter uncertainties and PSHA input combinations mentioned above are summarized in the logic tree as shown in Figure 6.



Weights for the depth to top of rupture, Z_{tor}

Magnitude range	Z_{tor} = 0	Z_{tor} = 2 km	Z_{tor} = 4 km
6.5 ≤ M ≤ 6.75	0.333	0.333	0.333
6.75 < M ≤ 7.0	0.5	0.5	–
7.0 < M	1.0	–	–

Figure 6. Logic tree used for PSHA. The weights for Z_{tor} are shown in the table.

PROBABILISTIC SEISMIC HAZARD ANALYSIS RESULTS

The PSHA was performed using EZ-FRISK v.7.37 (RISK-Engineering 2009) for Islamabad, the capital city of Pakistan (73.06˚E, 33.72˚N), and Peshawar (71.54˚E, 34.00˚N). Figure 7 and Figure 8 present the hazard curves (ground motion amplitude with respect to annual frequency of exceedance) for Islamabad and Peshawar, respectively, for assumed bedrock with 760 m/sec (i.e., NEHRP B/C boundary). The ground motion amplitudes (spectral accelerations) correspond to PGA (zero period), 0.2 sec, and 1.0 sec periods. Three return periods commonly employed in engineering practice are marked on the opposite y-axis of each figure. The return periods of 475, 975, and 2475 years correspond to probabilities of exceedance (PE) of 10%, 5%, and 2% in 50 years, respectively. The analysis yielded PGAs of 0.39g and 0.22g for a 475-yr return period in Islamabad and Peshawar, respectively. Peak ground accelerations are controlled largely by the distance from the fault. As Islamabad is located approximately 3 km from the MBT while Peshawar is located approximately 20 km from the nearest fault, we judge the PGAs to be reasonable. Although Islamabad is near the MBT fault, high ground accelerations were not predicted because the city is located on the foot wall side of the fault. For other seismic zones, the PGA and 1.0-sec spectral acceleration commonly are similar at most return periods. The PSHA results for Islamabad and Peshawar agree with this experience. The 0.2-sec spectral accelerations for Islamabad exceed 1.0g and 1.7g for the 475- and 2475-year return periods, respectively. These high accelerations indicate a significant seismic hazard in Islamabad, resulting in severe seismic risk because the city is densely populated and has a vulnerable infrastructure.

Figure 9 presents uniform hazard spectra (UHS) for three return periods. These plots are used to evaluate structural response at different natural periods. The spectral accelerations peak at a period of 0.2 sec. Figure 9 also compares the UHS for a 475-year return period with previous PSHA studies (Monalisa et al. 2007; NORSAR and PMD 2006; PMD and NORSAR 2006). In contrast to the current study, these other studies employed areal seismic source zones. For Peshawar, spectral accelerations from this and previous studies agree fairly well. In contrast, the spectral accelerations computed for Islamabad in this study are two to three times greater than those predicted by previous studies. As mentioned above, we believe the current results are more reasonable because Islamabad is approximately 3 km from an active fault.

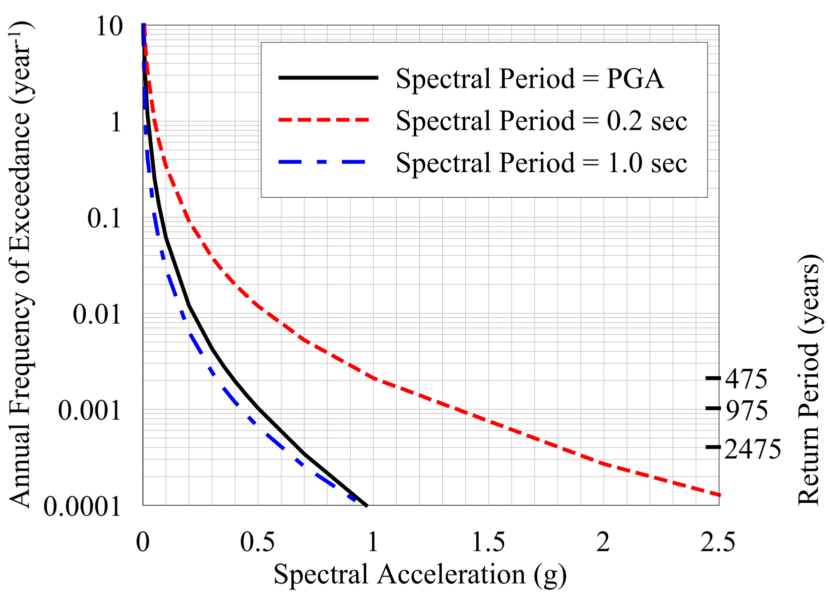


Figure 7. Hazard curve computed for Islamabad. Three return periods corresponding to their annual frequencies of exceedance are marked on the right y-axis.

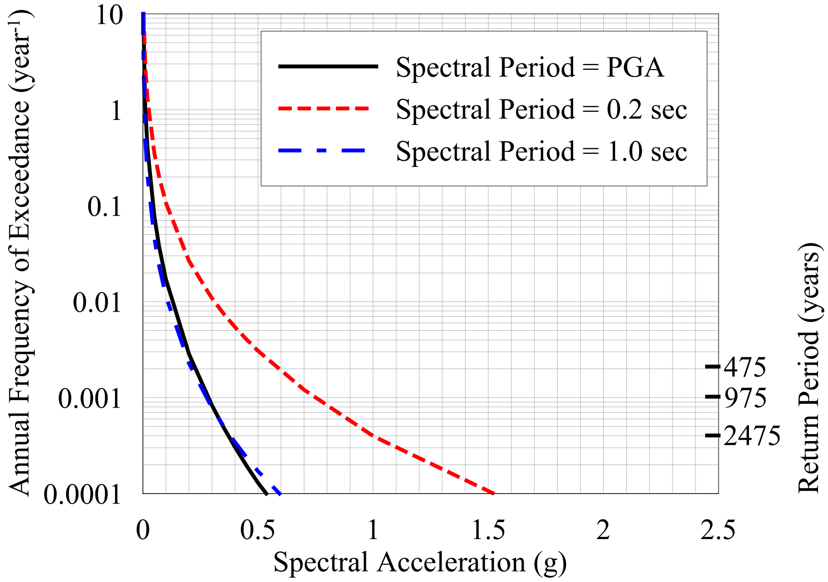


Figure 8. Hazard curve computed for Peshawar. Three return periods corresponding to their annual frequencies of exceedance are marked on the right y-axis.

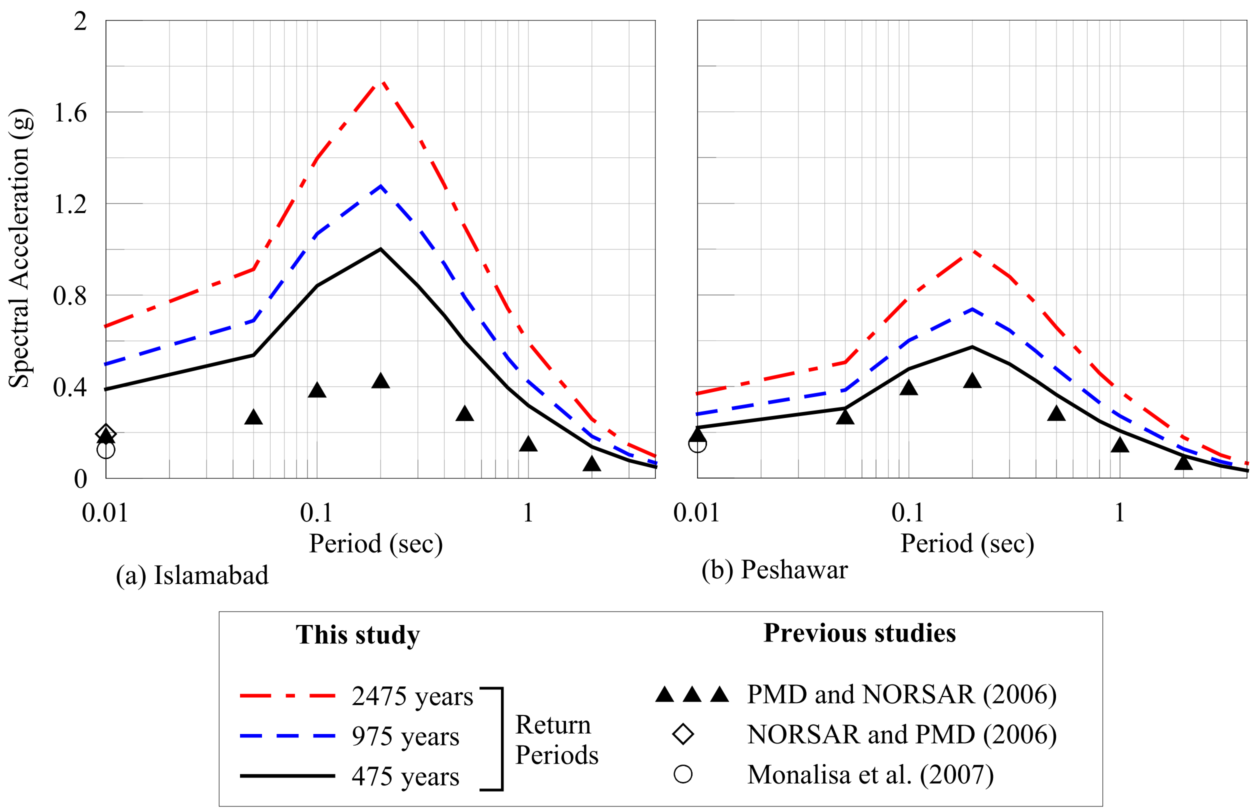


Figure 9. Uniform hazard spectra at three return periods for: (a) Islamabad; and (b) Peshawar. Spectral accelerations estimated by NORSAR and PMD (2006) and PMD and NORSAR (2006) at a 500-year return period and Monalisa et al. (2007) at a 475-year return period are included for comparison.

CONCLUDING REMARKS

While numerous catastrophic earthquakes like the 2005 Kashmir event frequently occur around the world, no reliable method exists to predict the exact timing of earthquakes, especially over short time periods. As a result, earthquake engineers focus on preventing significant earthquake loss by designing earthquake-resistant new structures and seismically-mitigating existing structures. These structural methods require proper seismic hazard analysis results. Therefore, it is critical that building codes do not underestimate earthquake hazard, especially for socio-economically important cities located close to faults, like Islamabad. A sound seismic hazard analysis requires careful characterization of individual faults, and this paper documents part of a larger probabilistic seismic hazard analysis (PSHA) for NW Pakistan that, for the first time, incorporates seismic characteristics of individually-mapped faults and fault zones. In the PSHA, we estimated for Islamabad a PGA of 0.39g and a 0.2 sec spectral acceleration of 1.00g at a 475-year return period, suggesting that this city is at significant seismic risk given its dense population and seismically-vulnerable infrastructure. This study also illustrates the numerous uncertainties that require assumptions because many source zones and faults are inadequately characterized at this time. Thus to improve seismic hazard predictions in Pakistan, more effort must be directed at sound characterization of known and (currently) unknown seismic sources.

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