Probabilistic Seismic hazard Analysis of Kathmandu City, Nepal

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ABSTRACT -Kathmandu is classified as a highly earthquake prone city of Nepal. The center of Kathmandu City is located in the vicinity of ten independent seismic source zones which in reality are active faults. This creates uncertainties in the size, location and the rate of recurrence of earthquakes. Probabilistic seismic hazard analysis 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. This study presents a PSHA of the center of Kathmandu city using the attenuation relationship given by Cornell et al (1979) in order to determine various levels of earthquake-caused ground motion that will be exceeded in a given future time period.

KEYWORDS -seismic source zone; active faults; recurrence of earthquakes; seismic hazard; attenuation relationship; earthquake-caused ground motion

1. INTRODUCTION

Kathmandu city has been subjected to frequent earthquakes of moderate intensities and about once in a century to disastrous earthquake of higher magnitude. Earthquake was first recorded in Nepal on June 7, 1255 AD when one third of the total population in Kathmandu were killed by a 7.7 Richter scale.

Magnitude-Frequency Data on Earthquakes in Nepal and the Surrounding Region (1911AD-1991AD)

	Earthquakes of magnitudes in Richter scale				
	5 to 6	6 to 7	7 to 7.5	7.5 to 8	>8
No. of events	41	17	10	2	1
Recurrence interval in years	2	5	8	40	81

Table 1: Earthquakes in Nepal (1911 to 1991)

Recent earthquakes near Kathmandu city are shown in figure1

Figure 1: Recent earthquakes near Kathmandu

- *Gangtok, Sikkim, India. October 3, 2013. Magnitude 5.3*
- *Banepa, Nepal. August 30, 2013. Magnitude 5.0*
- *Tulsipur, Nepal. June 28, 2013. Magnitude 5.0*
- *Tulsipur, Nepal. August 23, 2012. Magnitude 5.0*
- *Kishanganj, West Bengal, India. March 27, 2012. Magnitude 5.0*
- *Kathmandu, Nepal. November 12, 2011. Magnitude 4.2*
- *Gangtok, Sikkim, India. September 14, 2011. Magnitude 6.9*
- *Darjiling, West Bengal, India. June 3, 2011. Magnitude 5.0*
- *Kathmandu, Nepal. December 29, 2010. Magnitude 5.2*
- *Khandbari, Nepal. February 26, 2010. Magnitude 5.5*

The most destructive earthquake came on Jan 16, 1934 AD; the Great Nepal Bihar Earthquake of magnitude 8.4 that resulted in damage intensity of IX-X MMI in many parts of Kathmandu valley.

The seismic vulnerability of Nepal and particularly Kathmandu valley is clearly justified, however study of the seismic hazard potential of the valley has not been performed systematically. The seismic hazard potential of a site is identified by conducting probabilistic seismic hazard analysis and constructing hazard curves. Hazard curve is a graphical representation of seismic intensity parameter such as peak ground acceleration and its annual probability of exceedence. It requires the identification of seismic source zones affecting the site, rate of recurrence of earthquake at each source, distance from each source to the site, probability density function of magnitude and systematic synthesizing of these to obtain the probability of exceedence of certain peak ground acceleration at the site due to all sources in its vicinity.

2. NUMERICAL STUDY

The seismic hazard curve does not vary significantly across the length and breadth of the city due to its small size thus making it cogent to consider only the center of the city. The ten independent seismic source zones, near the center of Kathmandu, which in reality are active faults are characterized in table2.

Source Zone	EQ Sources (Faults)	Fault name	Fault type	Assumed $M_{S,max}$	Assumed $M_{w,max}$	a	b	Source to site distance (km)
1	HFF-1.10	Narayani River	R/RL	6.7	6.5	4.17	1	83
2	HFF-1.15	Dhalkebar	R	7.2	6.8	3.38	1	84
3	MBT-2.3	ArungKh.	R,N down	7.5	7.0	4.24	1	140
4	MBT-2.4	Narayani	R	7.0	6.7	4.17	1	78
5	MBT-2.5	Hetauda	R	7.3	6.9	4.17	1	38
6	MCT-3.3	GosaiKunda	R	7.5	7.0	4.17	1	21
7	HFF-1.13	Amlekhgunj	R	7.0	6.7	4.17	1	47
8	LH-4.10	Sunkoshi-RoshiKh.	Rt-lat-st-sl	6.7	6.5	4.17	1	68
9	MBT-2.6	Udaipur-Sunkoshi	Rev.norm	8.0	7.3	4.23	1	104
10	LH-4.7	Saptakoshi-Deomai	R	7.6	7.1	4.24	1	185

Table 2: Characteristics of seismic sources and source-to-site distance

2.1 Mean annual occurrence rate

The threshold magnitude is taken as 4.5 since smaller magnitude earthquakes are not believed to be capable of damaging structures and are thus unnecessary to consider for seismic hazard analysis. The mean annual occurrence rate of earthquake (υ) of magnitude larger than the threshold magnitude (m_o=4.5) calculated for each source using Guttenberg-Ritcher recurrence law is divided by 16.

$$\upsilon_i = \frac{10^{a-bm_0}}{16} \quad \text{(i = 1,2,3... 10 for 10 sources)}$$

where, a = overall occurrence rate of earthquake for each source

b = relative ratio of small and large magnitudes for each source

The mean annual occurrence rate of earthquake greater than magnitude 4.5 at each source is tabulated in Table3.

Source	
1	**0.02923**
2	**0.00474**
3	**0.03435**
4	**0.02923**
5	**0.02923**
6	**0.02923**
7	**0.02923**
8	**0.02923**
9	**0.03356**
10	**0.00947**

10X1

Table 3: Mean annual occurrence rate of 10 sources

2.2 Probability density function of magnitude

Each source is capable of producing earthquakes with a variety of magnitudes with an upper bound of maximum moment magnitude ($M_{w,max}$) and a common lower bound of the threshold magnitude (m_o = 4.5). The total range of earthquake magnitudes is divided into 6 equal intervals for all sources.

m_l-m_u	4.5 - 5.0	5.0 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	7.0 - 7.5
Mean(m)	4.75	5.25	5.75	6.25	6.75	7.25

Table 4: Discretization of earthquake magnitudes

Each interval is discretely represented by its mean value. If the value of maximum moment magnitude of any source lies within any particular interval, the interval will have an upper bound value equal to the same maximum moment magnitude. The distribution of the earthquakes of various magnitude is assumed to follow Bounded Guttenberg-Ritcher model.

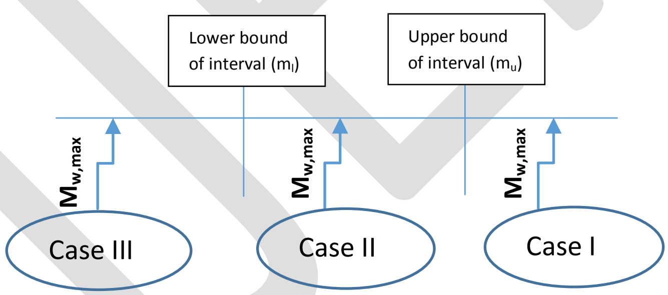

Figure 2: Position of $M_{w,max}$ in a particular interval

Case I : $M_{w,max} > m_u$

$$P(M = m) = P(m_l < m < m_u) = \frac{2.303 * b * e^{-2.303\, b\, (m - m_0)}}{1 - e^{-2.303\, b\, (M_{w,max} - m_0)}} * (m_u - m_l)$$

Case II : $M_{w,max} < m_u$ and $M_{w,max} > m_l$

$$P\left(M = \frac{m_l + M_{w,max}}{2}\right) = P(m_l < m < M_{w,max}) = \frac{2.303 * b * e^{-2.303\, b\, (\frac{m_l + M_{w,max}}{2} - m_0)}}{1 - e^{-2.303\, b\, (M_{w,max} - m_0)}} * (M_{w,max} - m_l)$$

Case III : $M_{w,max} < m_l$

P(M) = 0

The probability density function of magnitude for all the 10 sources are tabulated in table5 and plotted in figure3

	Magnitude						
Source	4.75	5.25	5.75	6.25	6.75	7.25	
1	**0.65400**	**0.20677**	**0.06537**	**0.02067**	**0.00000**	**0.00000**	
2	**0.65073**	**0.20574**	**0.06505**	**0.02056**	**0.00491**	**0.00000**	
3	**0.64952**	**0.20535**	**0.06493**	**0.02053**	**0.00649**	**0.00000**	
4	**0.65158**	**0.20600**	**0.06513**	**0.02059**	**0.00368**	**0.00000**	
5	**0.65005**	**0.20552**	**0.06498**	**0.02054**	**0.00583**	**0.00000**	
6	**0.64952**	**0.20535**	**0.06493**	**0.02053**	**0.00649**	**0.00000**	
7	**0.65158**	**0.20600**	**0.06513**	**0.02059**	**0.00368**	**0.00000**	
8	**0.65400**	**0.20677**	**0.06537**	**0.02067**	**0.00000**	**0.00000**	
9	**0.64850**	**0.20503**	**0.06482**	**0.02049**	**0.00648**	**0.00155**	
10	**0.64910**	**0.20522**	**0.06488**	**0.02051**	**0.00649**	**0.00065**	10X6

Table 5: Probability Density Function of magnitude P(M)

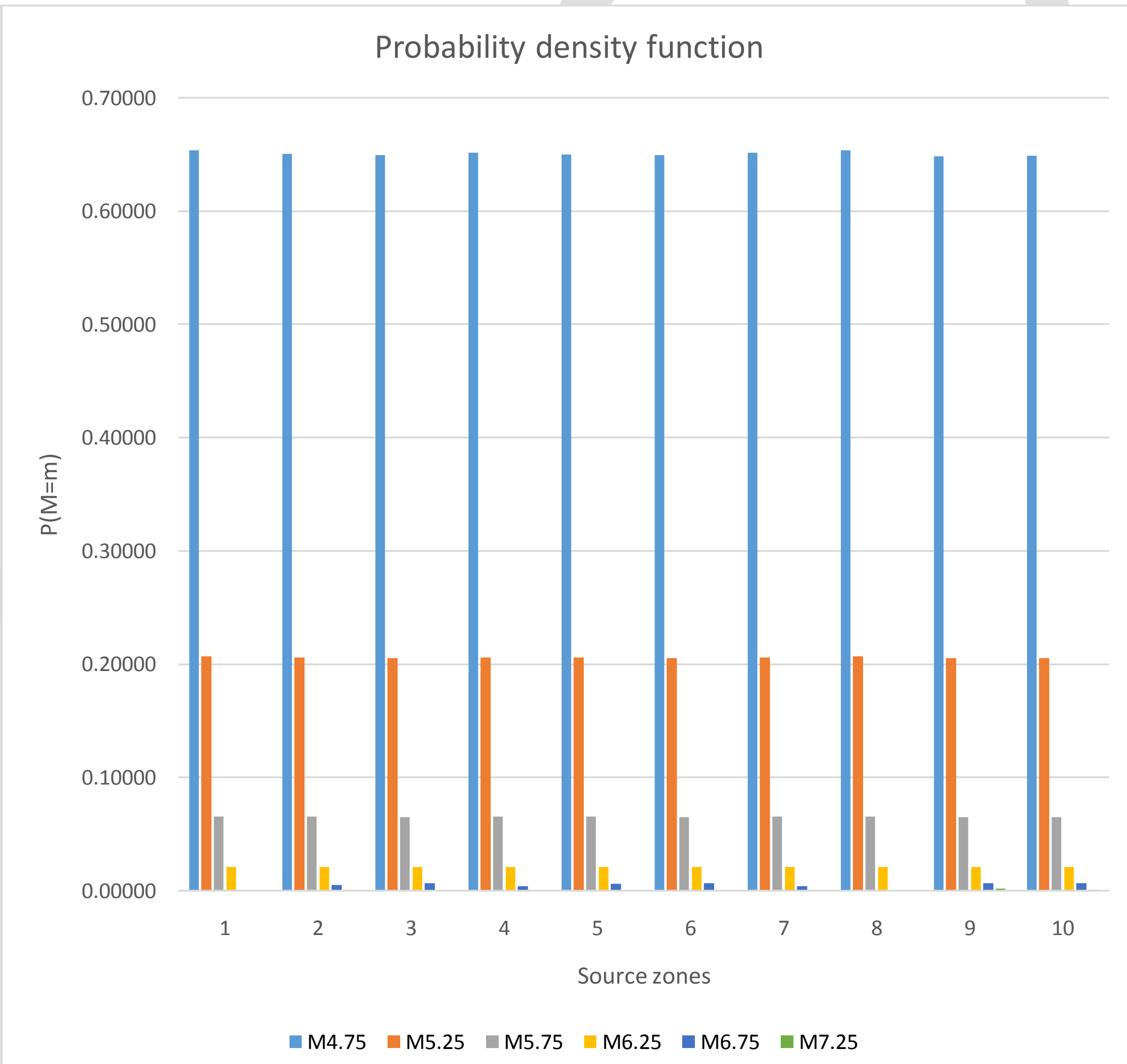

Figure 3: Probability density function of magnitude

2.3 Probability of exceeding certain Peak Ground Acceleration Level provided a fixed magnitude of earthquake

The attenuation relationship used for the Probabilistic Seismic Hazard Analysis is the one proposed by Cornell et al. (1979) for the mean of natural logarithm of Peak ground acceleration.

$$\ln PGA = 6.74 + 0.859\,M - 1.80\ln(R+25)$$

where, PGA is in gal and $\sigma = \sigma_{\ln PGA} = 0.57$

The natural log of PGA is normally distributed, so the conditional probability of exceeding any PGA level (PGA*) is,

$$P\,(PGA > PGA^* \mid M=m, R=r) = 1 - \phi\left(\frac{\ln PGA^* - \ln PGA}{\sigma}\right)$$

where, $\phi(\,)$ is the standard normal cumulative distribution function

A total of 60 PGA levels starting from 0.01g m/s^2 (9.81 gals) to 0.6g m/s^2 (588.6 gals), i.e., ln(PGA*) have been considered in this hazard analysis.

All the source zones are point sources, so each source to site distance R is known to be r, consequently the probability of R = r is 1 and the probability of $R \neq r$ is 0.

$$P(R = r) = 1 \text{ and } P(R \neq r) = 0$$

2.4 Probability of exceeding certain Peak Ground Acceleration Level

Since all continuous distributions for M and R have been discretized, so the total probability of exceeding certain PGA level is given by,

$$\lambda(PGA > PGA^*) = \sum_{i=1}^{n_s} \upsilon\,(M_i > m_0) \sum_{j=1}^{n_m}\sum_{k=1}^{n_R} P(PGA > PGA^* \mid m_j, r_k) P(M_i = m_j) P(R_i = r_k)$$

where, the range of possible M_i and R_i has been discretized to n_m and n_R intervals respectively. In this analysis, $n_s = 10$ sources, $n_m = 6$ and $n_R = 1$

$$\lambda(PGA > PGA^*) = \sum_{i=1}^{10} \upsilon\,(M_i > m_0) \sum_{j=1}^{6} P(PGA > PGA^* \mid m_j, r) P(M_i = m_j)$$

The total probability of exceeding certain PGA level is tabulated in table6.

λ(PGA>PGA*)

PGA* (times g)	All sources
0.01	**0.16788**
0.02	**0.10220**
0.03	**0.06760**
0.04	**0.04727**
0.05	**0.03427**
0.06	**0.02551**
0.07	**0.01940**
0.08	**0.01501**
0.09	**0.01179**
0.1	**0.00939**
0.11	**0.00757**
0.12	**0.00617**
0.13	**0.00508**
0.14	**0.00422**
0.15	**0.00354**
0.16	**0.00299**
0.17	**0.00254**
0.18	**0.00218**
0.19	**0.00187**
0.2	**0.00162**
0.21	**0.00141**
0.22	**0.00123**
0.23	**0.00108**
0.24	**0.00096**
0.25	**0.00085**
0.26	**0.00075**
0.27	**0.00067**
0.28	**0.00060**
0.29	**0.00054**
0.3	**0.00048**

PGA* (times g)	
0.31	**0.00043**
0.32	**0.00039**
0.33	**0.00035**
0.34	**0.00032**
0.35	**0.00029**
0.36	**0.00027**
0.37	**0.00024**
0.38	**0.00022**
0.39	**0.00020**
0.4	**0.00019**
0.41	**0.00017**
0.42	**0.00016**
0.43	**0.00014**
0.44	**0.00013**
0.45	**0.00012**
0.46	**0.00011**
0.47	**0.00011**
0.48	**0.00010**
0.49	**0.00009**
0.5	**0.00008**
0.51	**0.00008**
0.52	**0.00007**
0.53	**0.00007**
0.54	**0.00006**
0.55	**0.00006**
0.56	**0.00005**
0.57	**0.00005**
0.58	**0.00005**
0.59	**0.00004**
0.6	**0.00004**

60X1

Table6: $\lambda(PGA > PGA^{*})$ *for cumulative effect of all* 10 *sources*

2.5 Poisson's model

The temporal occurrence of earthquake is described by using Poisson's model since the events of earthquake occurrence are assumed to be independent of each other in time and space. The rate of exceeding a certain PGA level atleast once in a period of 't' years is given by,

$$P\ (N \geqslant 1) = 1 - e^{-\lambda t}$$

The rate or probability of exceeding a range of PGA levels atleast once in 1 year, 50 years and 100 years is tabulated in table7.

PGA* (times g)	**1-exp(-λt)** *All sources & t = 1yr*	**1-exp(-λt)** *All sources & t = 50yrs*	**1-exp(-λt)** *All sources & t = 100yrs*
0.01	**0.15454**	**0.99977**	**1.00000**
0.02	**0.09715**	**0.99396**	**0.99996**
0.03	**0.06537**	**0.96596**	**0.99884**
0.04	**0.04617**	**0.90591**	**0.99115**
0.05	**0.03369**	**0.81980**	**0.96753**
0.06	**0.02519**	**0.72077**	**0.92203**
0.07	**0.01921**	**0.62086**	**0.85625**
0.08	**0.01490**	**0.52783**	**0.77705**
0.09	**0.01172**	**0.44545**	**0.69248**
0.1	**0.00935**	**0.37475**	**0.60906**
0.11	**0.00754**	**0.31519**	**0.53104**
0.12	**0.00615**	**0.26556**	**0.46060**
0.13	**0.00507**	**0.22443**	**0.39849**
0.14	**0.00422**	**0.19039**	**0.34454**
0.15	**0.00353**	**0.16221**	**0.29811**
0.16	**0.00298**	**0.13883**	**0.25838**
0.17	**0.00254**	**0.11936**	**0.22447**
0.18	**0.00217**	**0.10308**	**0.19554**
0.19	**0.00187**	**0.08942**	**0.17085**
0.2	**0.00162**	**0.07791**	**0.14974**
0.21	**0.00141**	**0.06815**	**0.13165**
0.22	**0.00123**	**0.05985**	**0.11611**
0.23	**0.00108**	**0.05275**	**0.10271**
0.24	**0.00096**	**0.04666**	**0.09114**
0.25	**0.00085**	**0.04140**	**0.08109**
0.26	**0.00075**	**0.03686**	**0.07236**
0.27	**0.00067**	**0.03291**	**0.06474**
0.28	**0.00060**	**0.02946**	**0.05806**
0.29	**0.00054**	**0.02645**	**0.05220**
0.3	**0.00048**	**0.02380**	**0.04704**
0.31	**0.00043**	**0.02147**	**0.04248**
0.32	**0.00039**	**0.01941**	**0.03845**
0.33	**0.00035**	**0.01759**	**0.03486**
0.34	**0.00032**	**0.01597**	**0.03168**
0.35	**0.00029**	**0.01452**	**0.02883**
0.36	**0.00027**	**0.01323**	**0.02628**

	0.37	**0.00024**	**0.01207**	**0.02400**
	0.38	**0.00022**	**0.01104**	**0.02196**
	0.39	**0.00020**	**0.01011**	**0.02011**
	0.4	**0.00019**	**0.00927**	**0.01845**
	0.41	**0.00017**	**0.00851**	**0.01695**
	0.42	**0.00016**	**0.00782**	**0.01559**
	0.43	**0.00014**	**0.00720**	**0.01435**
	0.44	**0.00013**	**0.00664**	**0.01324**
	0.45	**0.00012**	**0.00613**	**0.01222**
	0.46	**0.00011**	**0.00566**	**0.01129**
	0.47	**0.00010**	**0.00524**	**0.01045**
	0.48	**0.00010**	**0.00485**	**0.00967**
	0.49	**0.00009**	**0.00449**	**0.00897**
	0.5	**0.00008**	**0.00417**	**0.00832**
	0.51	**0.00008**	**0.00387**	**0.00773**
	0.52	**0.00007**	**0.00360**	**0.00718**
	0.53	**0.00007**	**0.00335**	**0.00668**
	0.54	**0.00006**	**0.00312**	**0.00622**
	0.55	**0.00006**	**0.00290**	**0.00580**
	0.56	**0.00005**	**0.00271**	**0.00541**
	0.57	**0.00005**	**0.00253**	**0.00504**
	0.58	**0.00005**	**0.00236**	**0.00471**
	0.59	**0.00004**	**0.00220**	**0.00440**
	0.6	**0.00004**	**0.00206**	**0.00412**

Table 7: Rate of exceeding given PGA level atleast once in ’t’ years

2.6 Seismic Hazard Curve

Seismic hazard curve gives a strong basis for analyzing the seismic hazard potential at a site. The seismic hazard curve presented in figure4 gives the probability of exceedence of certain PGA level (from 0.01g to 0.6g where g = 9.81m/s^2) at the centre of Kathmandu city in 1 year, 50 years and 100 years.

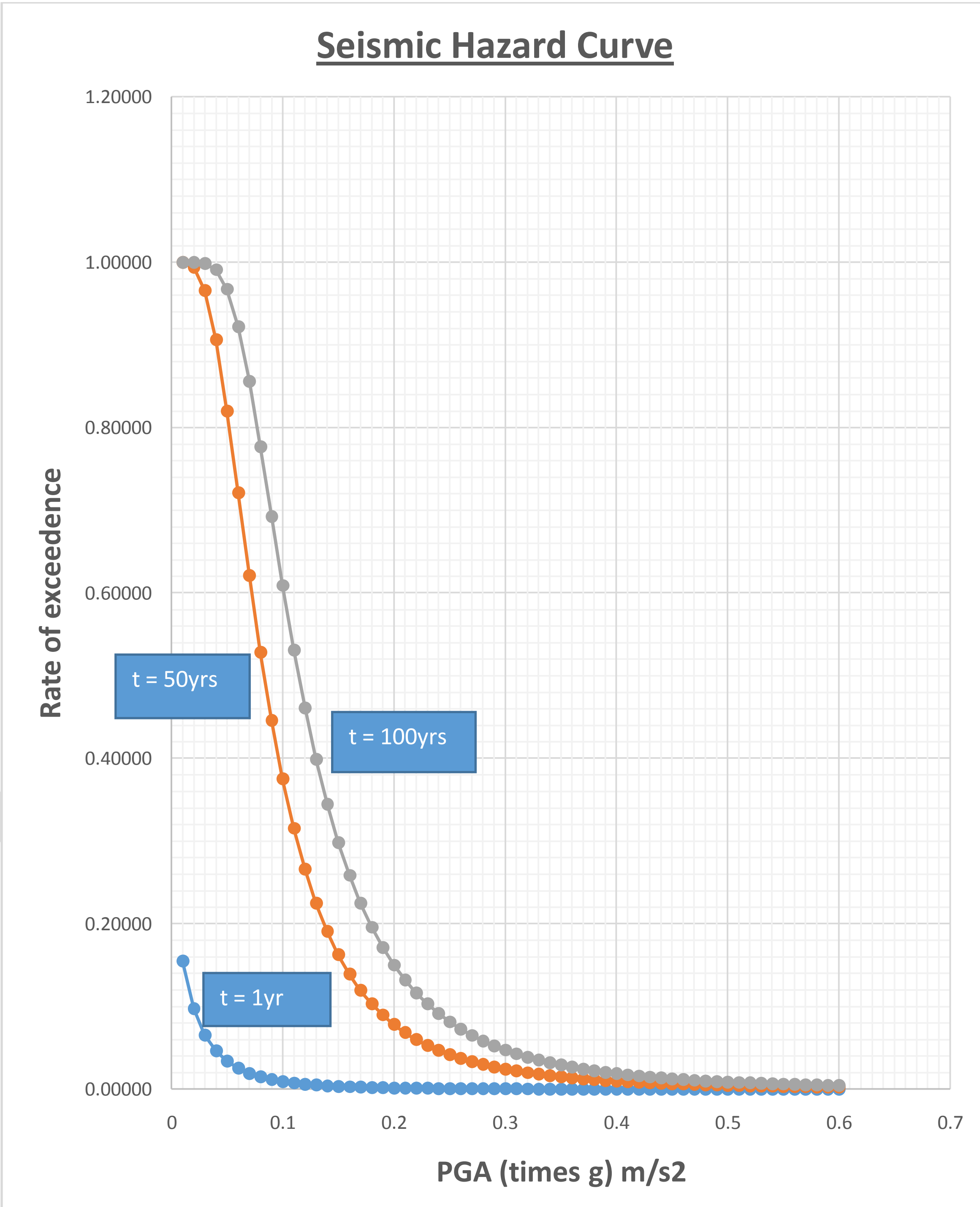

Figure 4: Seismic Hazard Curve

3. CONCLUSION

The probability density function for magnitude lends credible support to the frequent occurrence of moderate earthquakes and occasional occurrence of disastrous earthquakes. Earthquake source zone 9 (MBT-2.6) and 10 (LH-4.7) are more dangerous than the other sources as these two could induce magnitude above 7.0 which is disruptive. If a magnitude of around 7.5 occurs at Kathmandu, it can be inferred that source zones 9 and/or 10 have become dominant. Out of the two, source 9 is particularly threatening because it has greater mean annual occurrence rate of earthquake exceeding the threshold than source 10.

Similarly, the probabilistic seismic hazard analysis yields unsurprisingly high value of peak ground acceleration that is likely to occur any time in future at Kathmandu city. It is evident from the seismic hazard curve that there is a 2% rate of exceeding PGA of 0.31g in 50 years which is comparable to MMI scale of VIII and a 10% rate of exceeding PGA of 0.18g in 50 years comparable to MMI scale of VII. The PGA level of 0.5g to 0.55g is often compared with MMI scale IX (Violent earthquake) which was the case in 1934 AD (1990 BS) earthquake in Nepal. The probability of such an earthquake in Kathmandu once in a century is around 0.007 or 0.7%; so the apprehension for a "Big One" in Kathmandu is pertinent.

REFERENCES:

1 Kramer S.L. (1996). "Geotechnical Earthquake Engineering," Prentice Hall, Eaglewood Cliffs, New Jersey.
2 Cornell CA. (1968) "Engineering Seismic Risk Analysis." Bulletin of the Seismological Society of America; Vol. 58, No. 5, pp.1583-1606
3 Baker J.W. (2008). "An Introduction to Probabilistic Seismic Hazard Analysis (PSHA)", Version 1.3.
4 PremNathMaskey and T.K. Datta (2004). "Risk Consistent Response Spectrum And Hazard Curve For A Typical Location Of Kathmandu Valley" 13th World Conference on Earthquake Engineering
5 Earthquake Catalog in BCDP (1994).
6 URL: http://earthquaketrack.com
7 URL: http://www.nset.org.np