CONDITIONAL PROBABILITIES OF OCCURRENCE OF MODERATE EARTHQUAKES IN INDIAN REGION

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ABSTRACT :

A problem of increasing concern in India is the likelihood of occurrence of the next large earthquake in the areas where the last occurrence has crossed the return periods. The seismic hazard estimated based on the classical methodologies available as such do not consider the timing of the last occurrence of the damaging earthquake in the area while giving the probabilities of occurrence of the next such event. The average return period or recurrence interval as derived in the seismic hazard assessments does not in and of itself supply sufficient information of determining the probability of occurrence. It is also necessary to know the frequency distribution of recurrence intervals of a given magnitude or magnitude range. The conditional probabilities of occurrence of earthquakes have been estimated for the seismogenic sources in Indian region using the Weibull distribution. The estimations have been carried out by dividing the Indian subcontinent into 24 seismogenic sources. The cumulative probabilities estimation reveals that the zone Z2 and Z9 have the highest probabilities of occurrence of earthquake of maximum observed magnitude in the region. The return periods for these zones were estimated as 9 and 18 years while the last occurrence has been in the years 1940 and 1958, respectively. Ten zones namely, Z2, Z6, Z7, Z8, Z9, Z10, Z12, Z14, Z23 and Z24 out of the 24 zones were found to be having relatively higher conditional probabilities of occurrence of earthquake with maximum observed magnitude in the vicinity of 2005. Comparison of conditional probabilities with the classical approach emphasize that most of the part of the Indian continent is earthquake prone and it is necessary to consider the last occurrence of earthquake while estimating the seismic hazard for any region.

KEYWORDS: Conditional Probabilities, Weibul, Himalaya, Seismic hazard, seismicity

1. INTRODUCTION

The recent disastrous earthquakes of Sumatra (2004), Bhuj (2001), Chamoli (1999), Jabalpur (1997), Latur (1993), and Uttarkashi (1991) have caused widespread loss of life, property damage, and social and economic disruption. The assessment of seismic hazard is the first and fundamental step in the mitigation process, which reduces the disastrous economic and social effects of earthquakes. Seismic hazard, generally, is defined as the probable level of ground shaking associated with the recurrence of earthquakes. The assessment of seismic hazard is the first step in the evaluation of seismic risk, obtained by combining the seismic hazard with vulnerability factors (type, value and age of buildings and infrastructures, population density, land use, date and time of the day). Frequent, large earthquakes in remote areas result in high seismic hazard but pose no risk; on the contrary, moderate earthquakes in densely populated areas entail small hazard but high risk. The seismic hazard estimated based on the classical methodologies available as such do not consider the timing of the last occurrence of the damaging earthquake in the area while giving the probabilities of occurrence of the next such event (Shanker and Sharma, 1998, Sharma, 2003, Ameer et al , 2005). In Indian context where the seismicity rate varies spatially, a problem of increasing concern is the likelihood of occurrence of the next large earthquake in the areas where the last occurrence has crossed the return periods. The average return period or recurrence interval as derived in the seismic hazard assessments does not in and of itself supplies sufficient information of determining the probability of occurrence. It is also necessary to know the frequency distribution of recurrence intervals of a given magnitude or magnitude range. An endeavor has been made in the present study to estimate the conditional probabilities of occurrence of earthquakes based on Weibull distribution.

2. SEISMOTECTONICS OF INDIAN REGION

It is necessary to understand the physical process going on underneath before we try to assess the seismic hazard. Tectonic framework of the Indian subcontinent covering an area of about 3.2 million sq. km is spatio-temporally varied and complex. As a pre requisite for the seismic hazard studies, the study area has been divided into independent seismogenic source zones having individual characteristics. These source zones were chosen on the basis of Khattri et al. (1984) in which the whole country is divided into 24 source zones. Figure 1. shows the source zones considered in the study for seismic hazard assessment. The zone I consist of eastern coastal belt includes part of Mahanadi and Godavari graben. The major part of the zone comprises of Archean rocks and Precambrian fault systems. The general tectonic trend in this zone is in east-northeast direction. It swings in a southerly direction to parallel the curvature of the eastern margin of the Cuddapah basin (79°E, 15°N) and again turns to assume a North-easterly alignment in the area South of Madras (80.3°E, 13.1°N.) (Eremenko and Negi, 1968; Valdiya, 1973). The Zone 2 is the Western coast of India extending from Koyna on the south to Ahmedabad on the north has occasionally had moderate earthquakes. The Zone 3 consist of Kutch region is a major zone of shallow-focus seismic activity, second in activity only to the active plate boundary zones. The Zone 4 lies in the northeast-trending Arravali range, consists of rocks of the Archean Arravali and Delhi systems. The Zone 5 covers the Narmada –Tapi rift, a system of deep seated fault of regional significance (Naqvi et al., 1974). The Zone 6, 7 and 8 are in related to the Andaman-Nicobar Islands which were formed by the convergence of the Burmese and Indian crustal plates, resulting into an anticlinical welt with faults parallel to the island structure. The Zone 9 is the highly seismic region of Arakan Yoma fold belt constitutes of Tertiary and large thickness of Mesozoic rocks in which granite and ultra basic rocks were intruded (Krishnan, 1968). The Zone 10 is in the Bramhaputra valley which forms one of the most seismically active areas in the subcontinent. The Zone 11 is towards west of zone 10 constituting of the geosyclinal basin which is covered with alluvium. Zone 12 and 14 covers the Himalayan tectonic unit, which constitutes the world’s highest mountain chain, this area is not densely populated. Zone 15 is a low seismicity zone made of narrow belt having low magnitude earthquake foci parallel to the south of zone 12 in the westernmost area. Zone 16, 18, and 19 cover the entire length of Kirthar-Sulaiman mountain ranges in the northwest part of the Indian subcontinent while Zone 17 is consisting of alluvial- covered tract where shallow infrequent earthquakes take place. Zone 20, 21 and 22 lie at the northern edge of the Indian shield and are adjacent to the Himalaya tectonic. Zone 23 is a vast region constitute of changing geotectonic provinces and concerned seismicity, known as trans- Himalayan zone, having latitude 38° on the north and longitude 100° on the east. Zone 24 which is the Pamir knot, is well known for intense shallow seismic activity. This area is formed by the junction of several tectonic provinces, which have very complex geodynamic relationships: the Himalaya, the Tien- Sham, and the Kara Korum

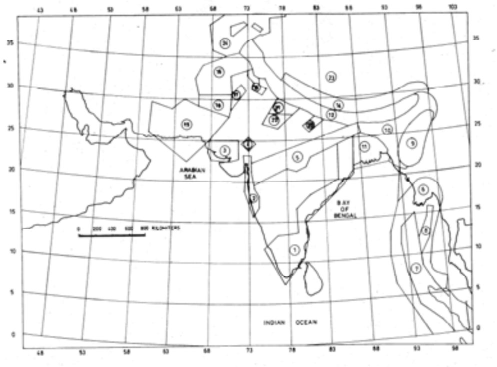

Fig. 1 Seismogenic source considered for the probabilistic seismic hazard analysis based on Khattri et al (1984)

3. WEIBULL DISTRIBUTION

It is well known that some of the statistical probability distributions are considered as representations of the actual recurrence interval distribution of earthquakes for a given magnitude range. The Weibull distribution developed by Weibull (1951) is based on a purely empirical basis for application to instances of failure of individual components of large systems. Hagiwara (1974) and Rikitake (1975) applied this distribution to data on crustal strain preceding large earthquakes. If the strain rate is approximately constant (as required by the time-predictable model), a Weibull distribution of “ultimate strain” will allow estimates of probability of occurrence (Johnston and Nava, 1985). The most simple statistical approach treats the statistical characteristics of earthquakes within a specified interval of geographical coordinates and the range of earthquake magnitude concerned. Some practical methods for earthquake prediction are reviewed in Rikitake (1976), and a thorough statistical discussion is in Vere-Jones (1970). Hagiwara (1974) and Rakitake (1976) presented a method of earthquake occurrence probability based on the Weibul model of statistics of crustal ultimate strain and the observed strain rate. Vere-Jones (1978) tried to calculate earthquake risk using the earthquake sequence statistics and stress evolution related to the earthquake cycle. Tripathi (2006) has estimated the probabilities of occurrence of large earthquake ($M\geq6.0$ and $M\geq5.0$) in a specified interval of time for different elapsed times on the basis of observed time-intervals between the large earthquakes ($M\geq6.0$ and $M\geq5.0$) using three probabilistic models, namely, Weibull, Gamma and Lognormal. In light of newly-acquired geophysical information about earthquake generation in the Tokai area, Central Japan, where occurrence of a great earthquake of magnitude 8 or so has recently been feared, probabilities of earthquake occurrence in the near future are reevaluated using the new Weibull distribution analysis of recurrence tendency of great earthquakes in the Tokai-Nankai zone (Tsuneji Rikitake (1999). Mazzoti and Adams (2004) use a Monte Carlo simulation to account for the uncertainties on probability, time and standard deviation and estimated the means and standard deviations for three possible distributions namely normal, lognormal,and Weibull (Mazzotti and Adams, 2004). Weibull statistics have been increasingly applied in seismic hazard research (e.g., Brillinger, 1982; Kiremidjian and Anagnos, 1984; Nishenko, 1985, Johnston and Nava, 1985, Ferraes, 2004, Kumar, 2006).The Weibull probability density function is given by

$$W(t) = \lambda v t^{v-1} \exp(-\lambda t^{v}) \qquad (1)$$

Where λ and v are constants that are related to T_r the mean time to failure, and to σ, the standard deviation, as follows (Hagiwara, 1974):

$$T_r = \int_o^{\infty} t w(t)\, dt = \lambda^{-1/v}\, \Gamma\left(\frac{v+1}{V}\right)$$
$$\frac{\sigma}{T_r} = \left[\Gamma\left(\frac{v+2}{v}\right) - \Gamma^2\left(\frac{v+1}{v}\right)\right]^{1/2} / \Gamma\left(\frac{v+1}{v}\right) \qquad (2)$$

where Γ is the gamma function. The v is often referred to as the shape parameter and increases as σ decreases. The λ is exponentially related to the mean rate of failure and increases as T_r decreases. It is of greater interest to know the probability of a large earthquake happening during some future time interval than to know the probability that it would have already happened by now (the present). For this reason we emphasize conditional rather than cumulative probabilities. Equation (2) may be directly integrated to obtain the cumulative Weibull probability:

$$W(T \le t) = \int_o^t w(\tau) = 1 - e^{-\lambda t^{\nu}} \tag{3}$$

which yields a conditional Weibull probability of

$$\mathrm{Wc}\,(\mathrm{t}, \Delta t) = \frac{\exp[-\lambda t^{\nu}] - \exp[-\lambda (t+\Delta t)^{\nu}]}{\exp[-\lambda t^{\nu}]} \tag{4}$$

4. CUMULATIVE AND CONDITIONAL PROBABILITIES FOR INDIAN REGION

One of the most important use of the Gutenberg Richter (GR) relationship is the estimation of return period based on the coefficients estimated from the seismicity of the seismogenic source zone (Gutenberg and Richter, 1954). The least square fitting of the line is used to obtained a and b coefficients of GR relationship. The a and b values thus computed are tabulated in Table I. The return periods of the various magnitudes for the seismogenic source zones are used to estimate the cumulative and conditional probabilities of occurrence earthquake using Weibull distribution. Frequency-magnitude analysis yields an estimated recurrence time T_r but do not estimate the variation of T_r as the seismic zone proceeds thorough many seismicity cycles. This variability is physically real and is exhibited by virtually all-seismic zones that have been identified as behaving in a cyclic manner (Johnston and Nava, 1985, Kumar, 2006). In the present study the standard deviation σ is allowed to vary from one third (33%) to two thirds (50 %) of T_r (Kumar, 2006). For σ in excess of $0.5T_r$ the very concept of the time-predictable seismicity model loses much of its meaning. The observed variability of the repeat times of magnitude 5 and 6 earthquakes in the historical record [Nuttle and Brill, 1981] suggests that σ should not be smaller than one third of $T_{r.}$ The Wiebull constants for different return periods used for the estimation of the probabilities are given in Table I. Fig. 2 shows the conditional probabilities estimation for the source zones Z4, Z5, Z7, Z19, Z21 and Z24. The conditional probability estimation for these source zones are shown as an example in Fig. 3. The Poissson distribution is also plotted in the figures for reference only.

Table I. The Wiebull constants for different return periods used for the estimation of the probabilities

Zones	**a**	**b**	**T_r, Years Mag. 6.0**	**Std dev. σ (% of T_r)**	**λ, Rate parameter**	**υ Shape parameter**
All India	7.91586	0.9675	4	33% 50%	7.956×10^{-3} 4.48×10^{-2}	3.30 2.10
Z_1	3.897	0.580	192	33% 50%	2.05×10^{-8} 1.25×10^{-5}	3.30 2.10
Z_2	4.081	0.522	9	33% 50%	4.96×10^{-4} 7.66×10^{-3}	3.30 2.10
Z_3	4.950	0.756	192	33% 50%	2.02×10^{-8} 1.236×10^{-5}	3.30 2.10
Z_4	1.362	0.1989	339	33% 50%	3.11×10^{-9} 3.75×10^{-6}	3.30 2.10
Z_5	3.432	0.5206	249	33% 50%	8.67×10^{-9} 7.20×10^{-6}	3.30 2.10
Z_6	5.777	0.805	57	33% 50%	1.15×10^{-6} 1.61×10^{-4}	3.30 2.10
Z_7	7.204	0.956	17	33% 50%	6.00×10^{-5} 2.0166×10^{-3}	3.30 2.10
Z_8	5.205	0.691	44	33% 50%	2.6×10^{-6} 2.76×10^{-4}	3.30 2.10
Z_9	5.750	0.716	18	33% 50%	5.4×10^{-5} 1.879×10^{-3}	3.30 2.10
Z_{10}	4.331	0.499	23	33% 50%	2.2×10^{-5} 1.063×10^{-3}	3.30 2.10
Z_{11}	2.198	0.301	205	33% 50%	1.6×10^{-8} 1.082×10^{-5}	3.30 2.10
Z_{12}	6.052	0.752	15	33% 50%	9.8×10^{-5} 2.73×10^{-3}	3.30 2.10

Z_{14}	5.577	0.745	40	33% 50%	3.7×10^{-6} 3.42×10^{-4}	3.30 2.10
Z_{15}	2.883	0.488	559	33% 50%	6×10^{-10} 1.317×10^{-4}	3.30 2.10
Z_{16}	3.958	0.4806	42	33% 50%	2.9×10^{-6} 2.96×10^{-4}	3.30 2.10
Z_{18}	6.643	1.022	154	33% 50%	4.2×10^{-8} 1.966×10^{-5}	3.30 2.10
Z_{19}	4.504	0.599	54	33% 50%	1.4×10^{-6} 1.317×10^{-4}	3.30 2.10
Z_{21}	2.575	0.437	557	33% 50%	6.1×10^{-10} 1.323×10^{-6}	3.30 2.10
Z_{22}	1.470	0.193	244	33% 50%	9.2×10^{-9} 7.506×10^{-6}	3.30 2.10
Z_{23}	6.512	0.8014	10	33% 50%	3.5×10^{-4} 6.197×10^{-3}	3.30 2.10
Z_{24}	7.376	0.955	11	33% 50%	2.3×10^{-4} 4.76×10^{-3}	3.30 2.10

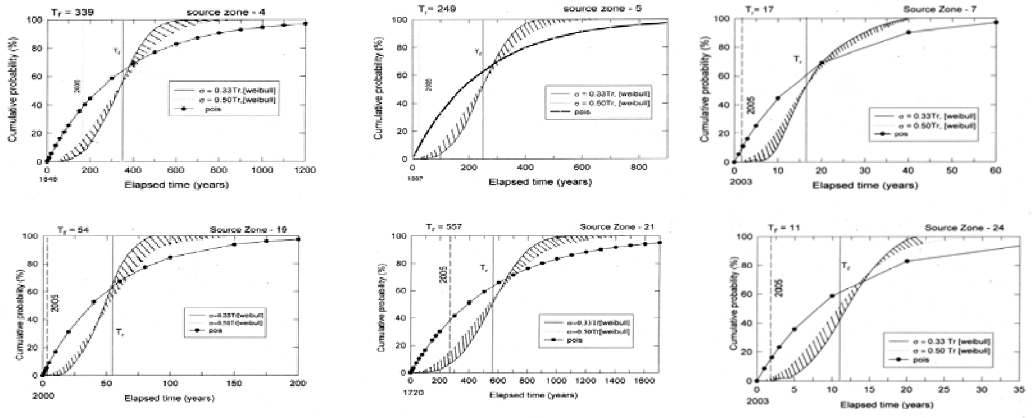

Fig. 2 Cumulative probabilities for various source zones. The return periods for the source zones are given as Tr at the top of the graph and is marked on the elapsed time axis along with the 2005 year.

Table II Cumulative probabilities of magnitude 6 as on 2005

Source Zones	**Year of last Earthquake**	**T_r (Years)**	**σ_1 = 0.33T_r**	**σ_2 = 0.50 T_r**	Weibull, %		Poisson, %
					σ_1	σ_2	
All India	**2004**	4	1.32	2	0.2	4.2	21
Z_1	1959	192	63.36	96	1.4	0.4	18
Z_2	1940	9	2.97	4.5	100	100	100
Z_3	1967	192	63.36	96	1.2	1.5	14
Z_4	1848	339	111.87	169.5	7.5	15	36
Z_5	1997	249	82.17	124.5	0	1.4	10.5
Z_6	1943	57	18.8	28.5	65.5	10.5	63
Z_7	2003	17	5.6	8.5	0	0.7	10.7
Z_8	1984	44	14.5	22	9.2	18.5	40
Z_9	1958	18	5.9	9	100	100	96.9
Z_{10}	1997	23	7.59	11.5	1.5	3.0	27.6
Z_{11}	1989	205	67.65	102.5	0	0.7	9.2
Z_{12}	1990	15	4.95	7.5	58.5	58.5	66
Z_{13}	-	-	-	-	-	-	-
Z_{14}	1993	40	13.2	20	0	40	23

Z_{15}	2001	559	184.47	279.5	0	0	3
Z_{16}	1999	42	13.86	21	1.5	3	13.8
Z_{17}	-	-	-	-	-	-	-
Z_{18}	1999	154	50.82	77	0	0	4.5
Z_{19}	2000	54	17.82	27	0	0	6
Z_{20}	-	-	-	-	-	-	-
Z_{21}	1720	557	183.8	278.5	6	15.4	38.5
Z_{22}	1960	244	80.5	122	0	3	73.8
Z_{23}	2003	10	3.3	5	0	1.5	66
Z_{24}	2003	11	3.6	5.5	0	1.5	15.4

Table III Conditional probabilities of magnitude 6 as on 2005

Source Zones	**Year of last Earthquake**	**T_r (Years)**	**Δt**	**Weibull, %**		**Poisson, %**
				σ_1	**σ_2**	
All India	2004	4	15	100	100	21
			50	100	100	
Z_1	1959	192	15	1	3	18
			50	4	12	
Z_2	1940	9	15	100	100	100
			50	100	100	
Z_3	1967	192	15	24	12	14
			50	65	36	
Z_4	1848	339	15	11	7	36
			50	34	24	
Z_5	1997	249	15	2	10	10.5
			50	6	30	
Z_6	1943	57	15	60	42	63
			50	100	90	
Z_7	2003	17	15	43	50	10.7
			50	100	100	
Z_8	1984	44	15	32	32	40
			50	100	87	
Z_9	1958	18	15	100	99	96.9
			50	100	100	
Z_{10}	1997	23	15	42	16	27.6
			50	100	100	
Z_{11}	1989	205	15	0	1.0	9.2
			50	0.2	8.0	
Z_{12}	1990	15	15	100	92	66
			50	100	100	
Z_{14}	1993	40	15	12	94	23
			50	93	100	
Z_{15}	2001	559	15	6	4	3
			50	20	14	
Z_{16}	1999	42	15	8	16	13.8
			50	82	75	
Z_{17}	-	-	-	-	-	-
Z_{18}	1999	154	15	0.5	2.0	4.5
			50	4.0	10.00	
Z_{19}	2000	54	15	4	9	6
			50	70	54	
Z_{20}	-	-	-	-	-	-
Z_{21}	1720	557	15	5	7	38.5
			50	20	11.5	
Z_{22}	1960	244	15	0.5	2.0	73.8
			50	3.0	9.0	
Z_{23}	2003	10	15	98	89	66
			50	100	100	
Z_{24}	2003	11	15	90	83	15.4
			50	100	100	

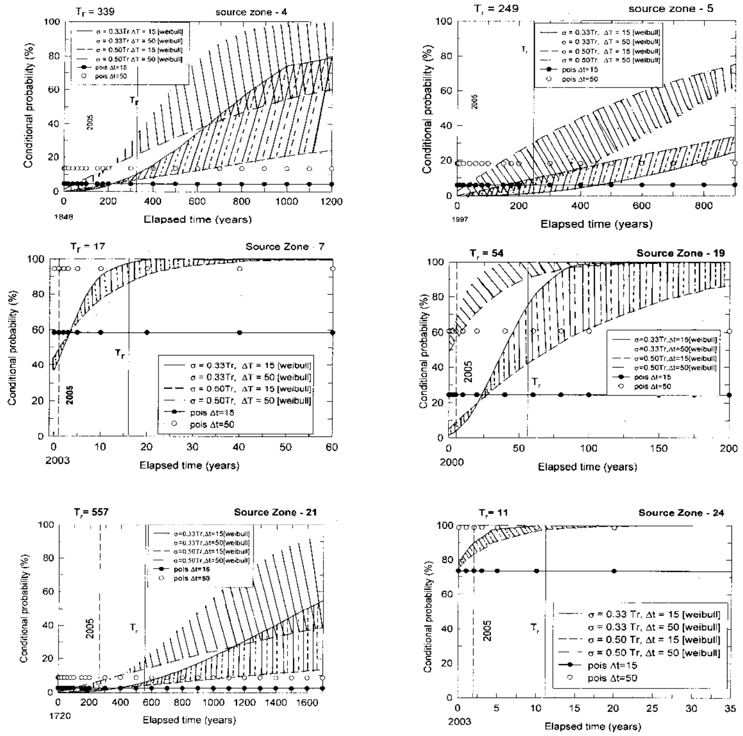

Fig. 3 Conditional probabilities for various source zones. The return periods for the source zones are given as Tr at the top of the graph. The Tr is also marked on the elapsed time axis along with the 2005 year.

5. RESULTS AND DISCUSSIONS

The cumulative probabilities as estimated in Table II reveals that the zone Z2 and Z9 have the highest probabilities of occurrence of earthquake of maximum observed magnitude in the region. The return periods for these zones were estimated as 9 and 18 years while the last occurrence has been in the years 1940 and 1958, respectively. The other two zones having higher probabilities are zone Z6 (0.65) and Z12 (58.5) where the return period was estimated as 57 and 15 years while the last occurrence was observed in the years 1943 and 1990 respectively. There are three zones namely Z13, Z17 and Z19 for which the data was less and no processing could be done further. There are six zones for which the probabilities are less than 10% while for other ten zones the probabilities were less than 1%. Similarly, the conditional probabilities were estimated for the two time intervals i.e., 15 and 50 years. The conditional probabilities estimated are given in Table III. Ten zones namely, Z2, Z6, Z7, Z8, Z9, Z10, Z12, Z14, Z23 and Z24 were found to be having highest probabilities of occurrence of earthquake with maximum observed magnitude in the vicinity of 2005. Tripathi (2006) has estimated the mean interval of occurrence of earthquakes and standard deviation as 20.18 and 8.40 years for $M \geq 5.0$ and 36.32 and 12.49 years, for $M \geq 6.0$, respectively, for Kutch region which is zone Z3 in the present study. For the earthquakes $M \geq 5.0$, the estimated cumulative probability reaches 0.8 after about 28 years for Weibull model in case of Tripathi (2006) while it is estimated as 36% for magnitude 6.0 for 50 year period (Table III). However, for the earthquakes $M \geq 6.0$, the estimated cumulative probability reaches 0.8 after about 47 years for all the models (including Weibull) while it reaches 0.9 after about 53, 54 and 55 years for Weibull, Gamma and Lognormal model (Tripathi, 2006). The zones Z12, Z14, Z20, Z21 and Z22 have been used by Shanker and Sharma (1998) for estimation of probabilistic seismic hazard based on Poissonian process and the probabilities for occurrence of magnitude 6.0 has been estimated between 60% to 85 % in next 50 years. The same zones gives the conditional probabilities estimated for next 50 years given the last occurrence of the earthquake gives the conditional probabilities for these zones as 100%, 100%, could not be estimated, 11.5% and 9% respectively. The comparison shows that it is necessary to consider the occurrence of the last earthquake while estimating the seismic hazard. Further, the analysis emphasize that most part of the Indian continent is earthquake prone and the conditional probabilities differ from the classical methods and should be considered while estimating the seismic hazard for Indian region.

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