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Estimation and implementations of conditional probabilities of occurrence of moderate earthquakes in India

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Abstract
The present paper presents conditional probabilities of occurrence of moderate earthquakes considering the likelihood of occurrence of the next large earthquake in the seismically active regions in India where the last such occurrence has crossed the return periods. The conditional probabilities have been estimated using Weibull distribution. The estimations have been carried out for 24 seismogenic sources earmarked in the Indian subcontinent. The cumulative and conditional probabilities have been interpreted with respect to the last earthquake occurrence in the time intervals of 15 and 50 years. Most of the seismically active regions are found to have lesser recurrence of earthquakes with specific magnitudes as compared with the estimations being carried out using classical probabilistic seismic hazard assessment approach.

Keywords: Conditional probability, earthquake hazard, Weibull distribution

Introduction

Most of the part of the Indian continent is earthquake prone and the recent disastrous earthquakes in the last decade have re-emphasized the need for more practical assessment of seismic hazard. Over the past few decades considerable effort has been focused on obtaining realistic assessments of seismic hazards (Kiremidjian & Shah, 1975; Mortgat & Shah, 1979; McCann, 1981; Shah & Dong, 1984; Wesnousky, 1986; Lamarre & Shah, 1988; Sharma, 2003; Ameer *et al.*, 2005; Raghukant & Iyengar, 2007; Mahajan *et al.*, 2009). Various approaches have been proposed for the evaluation of probability of occurrence and return period of large earthquakes (Kaila *et al.*, 1972; Lomnitz, 1974; Yegulap & Kuo, 1974). Seismic hazard studies of different tectonic regions have been carried out by various researchers - for the Aegean region (Bath, 1983; Markopoulos & Burton, 1985; Papadoupolos & Voidomatis, 1987; Papazachos, 1988; Papadoupolos & Kijko, 1991), for the western Norway coastal region (Kijko & Sellevoll, 1989, 1992) and for the various regions of India (Rao & Rao, 1979; Khattri *et al.*, 1984; Gupta & Srivastava, 1990; Sharma, 2003; Raghukant & Iyengar, 2007. Mahajan *et al.*, 2009).

Under the Global Seismic Hazard Assessment Programme (GSHAP), Bhatia *et al.* (1999) came out with a map of the whole of India showing PGA of the order 0.35 g to 0.4 g, based on probabilistic computation approach using Joyner and Boore (1981) attenuation relation. Sharma (2003) has estimated the seismic hazard of Garhwal Himalayan region in north India, and Tyagi (2006) estimated the seismic hazard potential for 50 years based on Artificial Neural Network (ANN) approach. One of the inputs in such endeavors is the probability of occurrence of earthquake with a specified magnitude which is then followed by estimation of ground motion using appropriate ground motion prediction equations.

The seismic hazard assessment, generally, do not consider the timing of the last occurrence of the damaging earthquake in the area while estimating the probabilities of occurrence of the next such event. In Indian context, where the seismicity rates vary spatially and temporally, 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 conditional probability of occurrence. It is of paramount interest to further estimate the frequency distribution of recurrence intervals of a given magnitude or magnitude range.

Weibull distribution, developed by Weibull (1951) based on a purely empirical basis for application to instances of failure of individual components of large systems, has been applied by Hagiwara (1974) and Rikitake (1975) 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 & Nava, 1985). A review was presented by Rikitake (1975) and Vere-Jones (1970). Recently, Tripathi (2006) estimated the probabilities of occurrence of large earthquake ($M \geq 6.0$ and $M \geq 5.0$) in a specified interval of time for different elapsed times on the basis of observed time-intervals between the large earthquakes ($M \geq 6.0$ and $M \geq 5.0$) using three probabilistic models, namely, Weibull, Gamma and Lognormal. Mazzoti and Adams (2004) used 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 & Adams, 2004). Weibull statistics have been used very often in estimating the recurrence periods of

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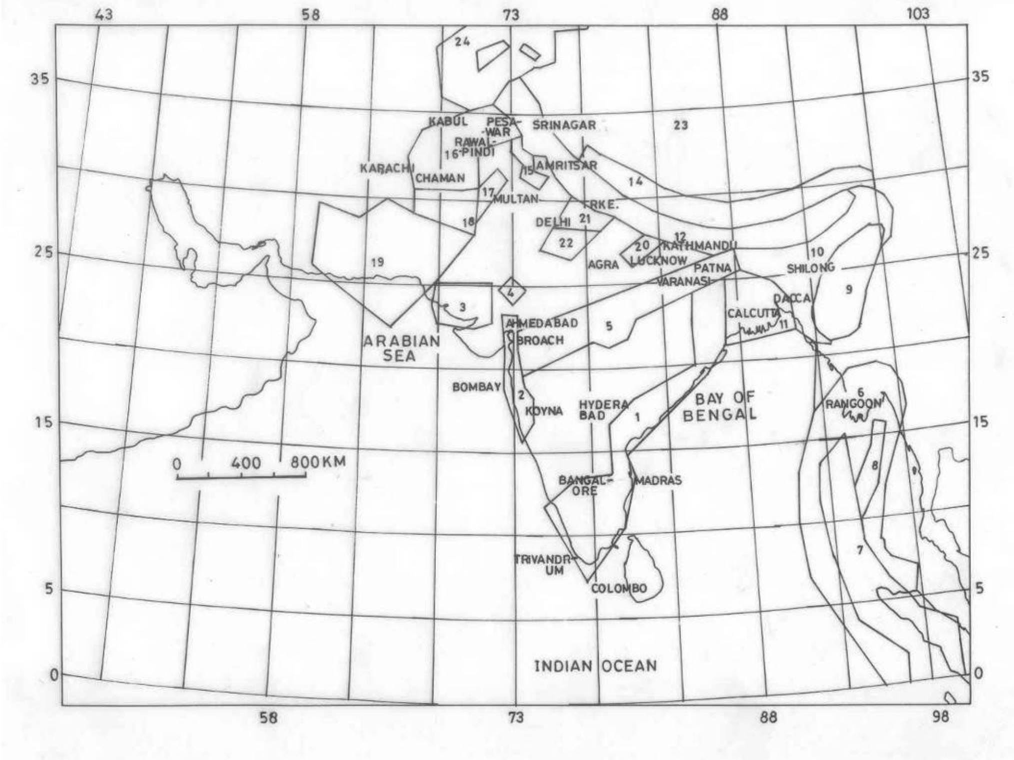

Fig. 1. Seismogenic source considered for the probabilistic seismic hazard analysis based on Khattri et al. (1984)

seismic events in active seismic zones (e.g., Brillinger, 1982; Kiremidjian & Anagnos, 1984; Nishenko, 1985; Johnston & Nava, 1985; Ferraes, 2004; Kumar, 2006). An endeavor has been made in the present study to estimate the cumulative conditional probabilities of occurrence of earthquakes based on Weibull distribution considering the occurrence of the last earthquake in the region of interest.

Seismotectonics of Indian region

In the present study recurrence periods of seismic events have been carried out for the Indian sub continent most part of which is earthquake prone as revealed in the seismic zoning map of India provided by IS-1893-2002. Before carrying out the seismic hazard assessment for a region seismotectonic modeling is carried out to earmark the independent seismogenic sources. Understanding of seismotectonics for different regions of India has gained enormous importance in the recent years as it is now recognized that no part of India is completely free from earthquake and there happens to be a constant threat from both plate-margin and intraplate earthquakes. The past earthquake occurrence in the Himalayas including Chamoli, Uttarkashi and Muzzaffarabad earthquake and the shield region including Latur, Jabalpur and Bhuj has demonstrated the sporadic spatial distribution of the damaging earthquakes. Tectonic framework of the Indian subcontinent covering an area of about 3.2 million sq. km is spatio-temporally varied and complex. The seismic hazard is generally carried out on the independent seismogenic sources. As a pre requisite for the assessment of seismic hazard, the whole country is divided into independent seismogenic source zones having individual characteristics pertaining to geological, geophysical and tectonic setup along with associated earthquakes events. Khattri *et al*. (1984) divided the whole Indian region into 24 independent seismogenic source zones. The division was based on the geological and tectonic setup of the area, past seismicity and other geophysical anomalies. We considered the seismotectonic model of Khattri *et al.* (1984) along with the models given by GSHAP (Bhatia *et al*.,1999; Sharma, 2003; Raghukant & Iyengar, 2007; Mahajan *et al*., 2009). Seismogenic model thus prepared has been shown in Fig. 1. The seismicity catalogue compiled and prepared by Kumar (2006) from various sources like India Metrological Department, United States geological Survey, International Seismological Commission and other published reports have been considered in the present study. The homogenized catague in surface wave magnitude checked for completeness and declustered for independent events as prepared by Tyagi, 2006 has been considered in the present study. The seismic events have been associated with the seismogenic source zones based on their geographical location. The seismic hazard is then evaluated independently for each of the seismogenic source zones.

Based on the above discussions the independent seismogenic sources have been marked as *Zones* as given in Fig. 1. *Zone 1* consists of eastern coastal belt including parts of Mahanadi and Godavari garbens. The general tectonic trend in this zone is in an ENE direction. *Zone 2* is the Western coast of India extending from Koyna on the south to Ahmedabad on the north and has experienced occasionally moderate earthquakes. The main feature of the geology of the region is the extensive lava flows, known as the Deccan traps of the late Mesozoic-early tertiary age (Raju, 1968; Avasthi *et al*., 1971). *Zone 3* encompasses Kutch region and is a major zone of shallow-focus seismic activity, second in activity only to the active plate boundary zones. The major tectonic features lie in the WNW direction and within these features block faulting has formed a system of nearly east-trending grabens and ridges. *Zone 4* lies in the northeast-trending Arravali range and consists of

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Table 1. The GR parameters and Wiebull constants for different return periods used for the estimation of the probabilities

Zones	Gutenberg Richter parameters		T_r, Years Mag. 6.0	λ Rate parameter	
	a	b		σ - 33% of T_r	σ - 50% of T_r
All India	7.91586	0.9675	4	7.956×10^{-3}	4.48×10^{-2}
Z_1	3.897	0.580	192	2.05×10^{-8}	1.25×10^{-5}
Z_2	4.081	0.522	9	4.96×10^{-4}	7.66×10^{-3}
Z_3	4.950	0.756	192	2.02×10^{-8}	1.236×10^{-5}
Z_4	1.362	0.1989	339	3.11×10^{-9}	3.75×10^{-6}
Z_5	3.432	0.5206	249	8.67×10^{-9}	7.20×10^{-6}
Z_6	5.777	0.805	57	1.15×10^{-6}	1.61×10^{-4}
Z_7	7.204	0.956	17	6.00×10^{-5}	2.0166×10^{-3}
Z_8	5.205	0.691	44	2.6×10^{-6}	2.76×10^{-4}
Z_9	5.750	0.716	18	5.4×10^{-5}	1.879×10^{-3}
Z_{10}	4.331	0.499	23	2.2×10^{-5}	1.063×10^{-3}
Z_{11}	2.198	0.301	205	1.6×10^{-8}	1.082×10^{-5}
Z_{12}	6.052	0.752	15	9.8×10^{-5}	2.73×10^{-3}
Z_{14}	5.577	0.745	40	3.7×10^{-6}	3.42×10^{-4}
Z_{15}	2.883	0.488	559	6×10^{-10}	1.317×10^{-4}
Z_{16}	3.958	0.4806	42	2.9×10^{-6}	2.96×10^{-4}
Z_{18}	6.643	1.022	154	4.2×10^{-8}	1.966×10^{-5}
Z_{19}	4.504	0.599	54	1.4×10^{-6}	1.317×10^{-4}
Z_{21}	2.575	0.437	557	6.1×10^{-10}	1.323×10^{-6}
Z_{22}	1.470	0.193	244	9.2×10^{-9}	7.506×10^{-6}
Z_{23}	6.512	0.8014	10	3.5×10^{-4}	6.197×10^{-3}
Z_{24}	7.376	0.955	11	2.3×10^{-4}	4.76×10^{-3}

rocks of the Archean Arravali and Delhi systems. *Zone 5* covers the Narmada –Tapi rift, a system of deep seated fault of region al significance (Naqvi *et al.*, 1974). *Zone 6, 7, and 8* encompasses Andaman-Nicobar Islands formed by the convergence of the Burmese and Indian crustal plates, resulting into an anticlinical belt with faults parallel to the island structure. Seismicity band trending in the north-northeast direction on the inner side of the island arc system has been treated as zone 8. Only shallow focus earthquakes are occurred here. *Zone 9* constitutes one of the highly seismic zone Arakan Yoma fold belt constitutes of Tertiary and large thickness of Mesozoic rocks in which granite and ultra basic rocks were intruded (Krishnan, 1968). *Zone 10* is the Bramhaputra valley which forms one of the most seismically active areas in the subcontinent.

To the southwest of zone 10 is the *Zone 11* which constitutes the geosyclinal basin which is covered with alluvium. Due to the thick layer of the sedimentary cover no structure is seems to be on the surface. Geophysical survey has revealed a system of normal faults in the sediments trending in a North-northeast direction with a hinge zone passing close to the Calcutta (Sengupta, 1966). This area seems to have more seismicity in the past centuries, but the current seismicity is relatively low. The highest recorded epicentral intensity is X in 1737, IX in 1842, VII in 1886 (Oldham, 1883).

Zone 12 and 14 covers the Himalayan tectonic unit, which constitutes the world's highest mountain chain. Zone 12 covers the central Himalaya range, which is close to the Main Central Thrust which is the main locale of seismicity. The principle seismic zone is zone 12 which spread along the entire length of the Himalaya tectonics and zone14 lies to the secondary seismic belt to the North. Seismicity in zone 14 decreases towards the west. In zone 12 many major earthquake occurred in the past years. The largest 1905 Kangra earthquake of magnitude 8.6 occurred and is related with the southern boundary of this zone, which is associated with the MBT. Another 1934 Bihar earthquake of M=8.4 occurred at the boundary of this zone close to zone 5 about 1300 km to the east. *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. This area is covered with alluvium which contains thick sediments of Miocene lying over the basement complex. : The three zones namely *Zone 16, 18, 19* cover the entire length of Kirthar-Sulaiman mountain ranges in the northwest part of the Indian subcontinent. Of the three zones, zone 19 is the most active zone. Zone18 spans the arcuate ranges. The maximum magnitude recorded in zone 16, 18, and 19 are 6.4, 7.5, and 8.3, respectively. *Zone 17* consists of alluvial- covered tract where shallow infrequent earthquakes take place. This zone represents a localized group of earthquakes, which extends from zone 18 to the northeast direction. The maximum of 6.4 is reported here.

The three zones namely *Zone 20, 21,* and *22* lie at the northern edge of the Indian shield and are adjacent to the Himalaya tectonic. Maximum parts of these areas are covered by alluvium and sediments of the Sindhu Ganga basin; whereas the geology is tending towards the southwest. Zone 21 and 22 meet at the northeast end of the north- northeast-trending Aravalli rocks. The largest reported earthquake in the past year is having a magnitude about 6. Similarly zone 20 also have low-magnitude seismicity and is concerned with Northeast trending faults in the basement. *Zone 23* is a vast region consisting of changing geotectonic provinces and concerned seismicity, known as Trans- Himalayan zone, having latitude 38° on the north and longitude 100° on the east. It has been regarded as single source zone. *Zone 24* is the Pamir knot which 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. This area experienced four great earthquakes of magnitude greater than 8 in the past years, the largest being 8.6.

Weibull distribution

It is well known that some of the statistical probability distributions are considered as representations of the

Table 2. Summary of cumulative probabilities for the year 2005 using Weibull distribution. The results of Poisson distribution are shown for reference

Source Zones	Year of last Earthquake	T_r (Years)	$\sigma_1 = 0.33T_r$	$\sigma_2 = 0.50\ T_r$	Probabilities using Weibull		Poisson, %
					σ_1	σ_2	
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_{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

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 & Nava, 1985). The simplest 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 (1975), and a thorough statistical discussion is given 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) estimated the probabilities of occurrence of large earthquake ($M \geq 6.0$ and $M \geq 5.0$) in a specified interval of time for different elapsed times on the basis of observed time-intervals between the large earthquakes ($M \geq 6.0$ and $M \geq 5.0$) 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 were reevaluated using the new Weibull distribution analysis of recurrence tendency of great earthquakes in the Tokai-Nankai zone (Rikitake (1999). Mazzoti and Adams (2004) used 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 & Adams, 2004). Weibull statistics have been used very often in estimating the recurrence periods of seismic events in active seismic zones (e.g., Brillinger, 1982; Kiremidjian & Anagnos, 1984; Nishenko, 1985; Johnston & Nava, 1985; Ferraes, 2004; Kumar, 2006).

The Weibull probability density function is given by (Johnston & Nava, 1985; Parvez & Ram, 1999)

$$W(t) = \lambda \nu t^{\nu-1} \exp(-\lambda t^{\nu}) \quad (1)$$

Where λ and ν are constants and t is the time interval in years between successive events. Hagiwara, (1974) related the constants λ and ν to T_r (return period) and to σ (standard deviation) as follows:

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

where Γ is the gamma function. The ν is often referred to as the shape parameter and increases as σ decreases. The λ is exponentially related to T_r 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 (Johnston & Nava, 1985):

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

which yields a conditional Weibull probability of

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

Estimation of cumulative and conditional probabilities for Indian region

One of the most important uses of the Gutenberg Richter (GR) relationship is the estimation of return period

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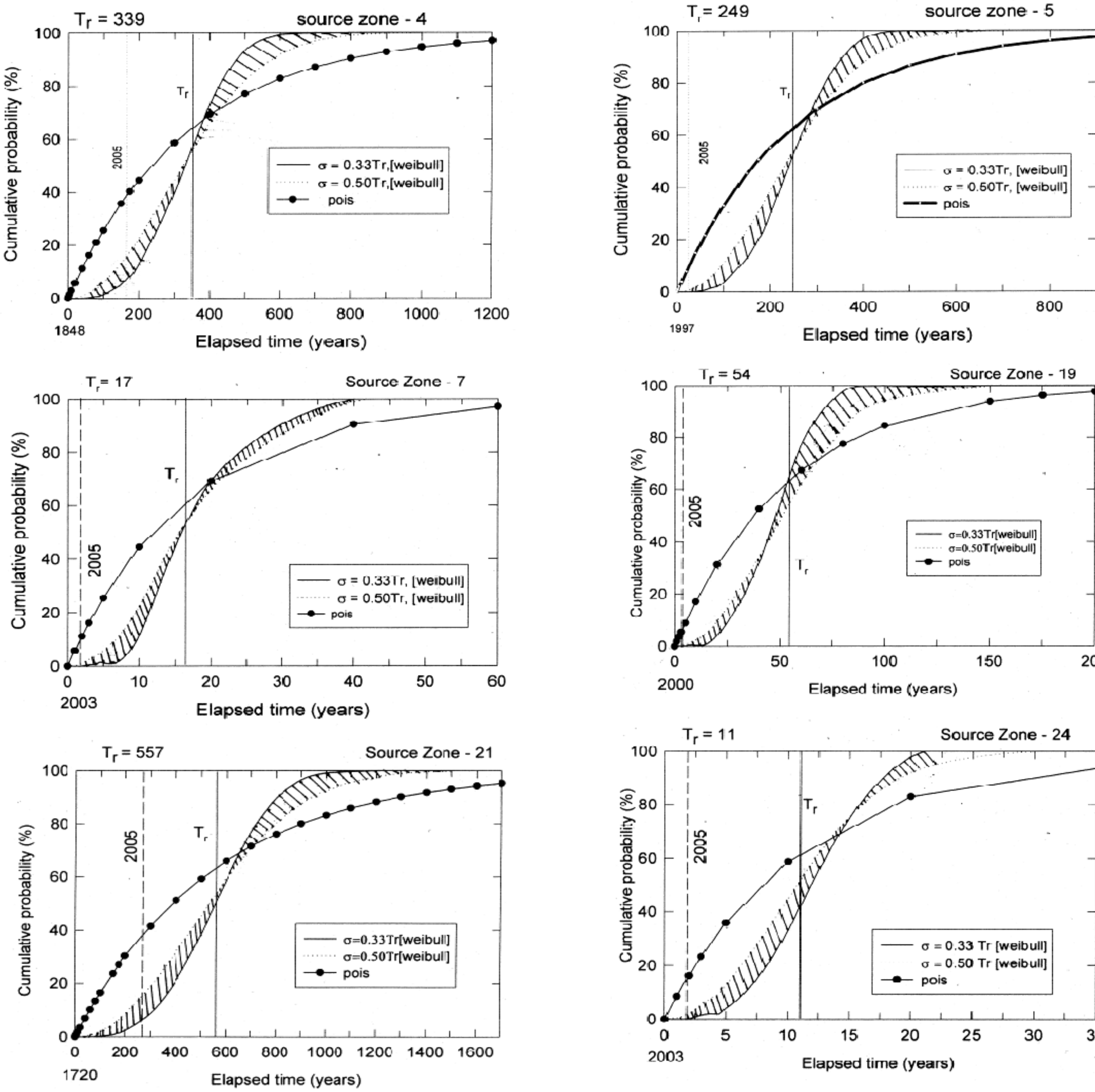
based on the coefficients estimated from the seismicity of the seismogenic source zone (Gutenberg & Richter, 1954). The ‘a’ and ‘b’ coefficients of GR relationship were estimated for all the seismogenic sources and are tabulated in Table 1. The estimated mean return periods for various magnitudes pertaining to the earmarked independent seismogenic source zones were then used to estimate the cumulative and conditional probabilities of occurrence earthquake using Weibull distributions.

Frequency-magnitude analysis carried out as above yields an estimate of 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 (Kumar, 2006; Tyagi, 2006). The earthquake events associated with each of the seismogenic source zones provide not only the information about a and b values but also the variation in T_r. For most of the seismogenic sources the data is not complete even for a

Fig. 2. Cumulative probabilities for various source zones using Wiebull distribution. 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



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single return period of the observed maximum magnitude prohibiting the estimation of variability in T_r. Using lesser data for the estimations may lead to incorporation of errors in the estimations and therefore, 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) which may accommodate the errors in a and b values and in turn the T_r . 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 (Nuttli & Brill, 1981) suggests that σ should not be smaller than one third of T_r. The shape parameter 'υ' has been estimated as 3.30 and 2.10 for standard deviation of 33% and 50% respectively (Johnston and Nava, 1985) and rate parameter 'λ' for all zones has been estimated using equation 2 and is given in Table I along with the combined zone as All India zone for comparison purpose.

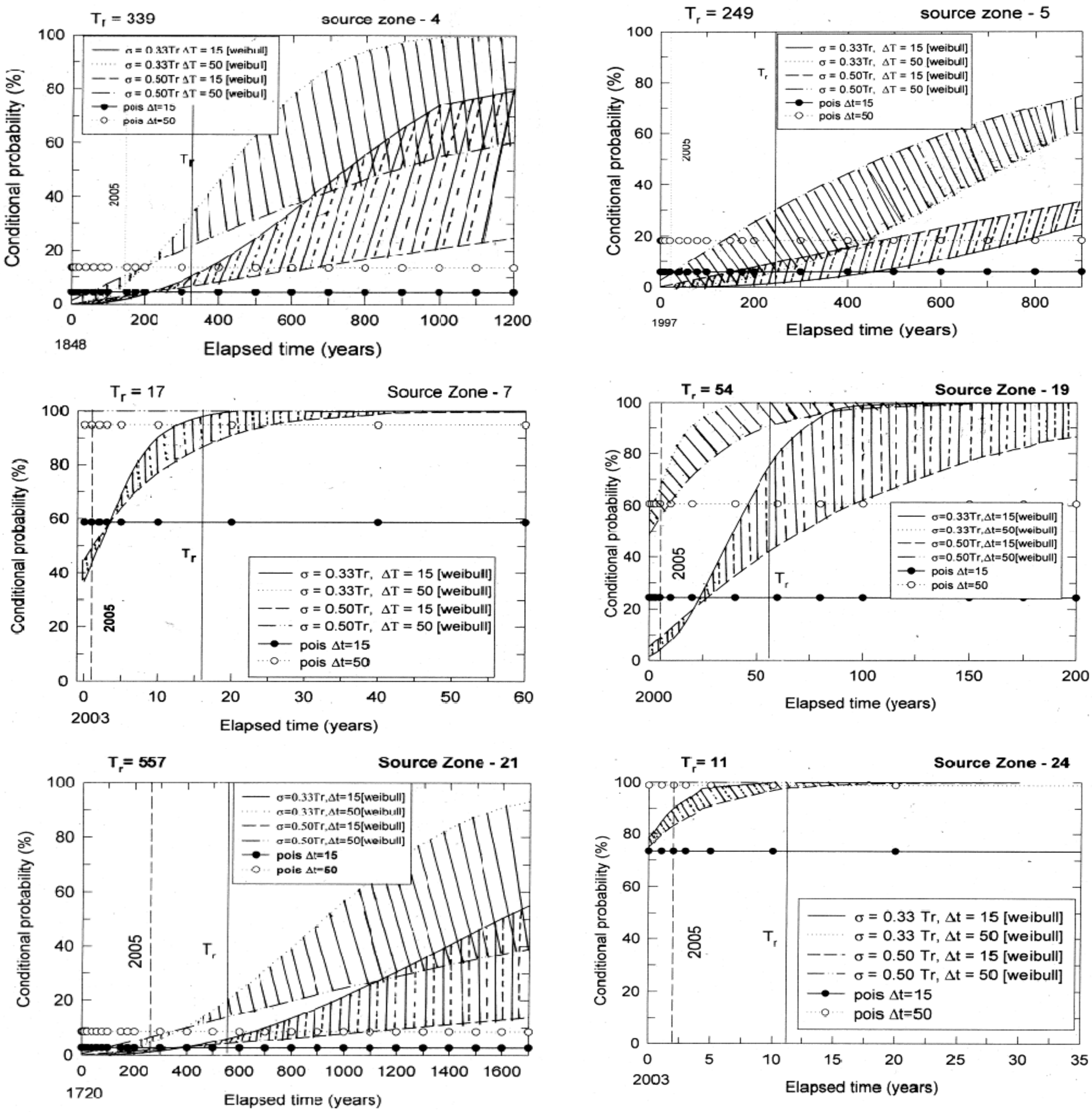
The cumulative probabilities have been estimated using Weibull distribution (equation 3) for all the seismogenic sources. For example the cumulative probabilities estimation for the seismogenic source zones Z4, Z5, Z7, Z19, Z21 and Z24 have been shown in Fig.2. The return periods for the source zones are given as Tr at the top of the graphs and is also marked on the elapsed time axis along with the test year which is considered as 2005 in the present case. The area bounded by the standard deviation being assumed as 33% and 50% of T_r has been hatched in the figure. For comparison the cumulative probabilities using Poissonian distribution have also been shown. For example, seismogenic zone 4 (Fig.1 for source location) lies in the northeast-trending Arravali range, which consists of rocks of the Archean Arravali and Delhi systems. The seismicity in this zone consists of low magnitude shallow focus events. An earthquake was reported in Mount Abu (I_o=VII) in 1848. An earthquake with M=5 occurred near Mt. Abu (72.4^{0}E, 24.8^{0}N) in 1969. For this seismogenic source the mean return period has been estimated as 339 years (also shown by a line on the elapsed time axis), which in turn gives about 112 years and 170 years for the standard deviations assumed as 33% and 50% (Table 2) and the cumulative probabilities estimated for these two periods have been found to be 7.5% and 15% respectively. The same has been estimated to be 36% based on the Possoinain distribution.

Similarly, seismogenic zone 5 covers the Narmada – Tapi rift, a system of deep seated fault of region al significance (Naqvi *et al*., 1974). Considerable vertical movements on these faults have created wedges of basement that are surrounded by younger geological formations. Although the rift belongs to Precambrian age (McConnell, 1974), there may lie young faulting along some segment; for example, Pleistocene contains Broach area faulting (Auden, 1959). The other significant earthquakes noticed in this zone are Son Valley earthquake (81.0^{0}E, 23.5^{0}N) of 1927 (M=6.5), Satpura earthquake (75.7^{0}E, 21.5^{0}N) of 1938 of M=6.3 and the Balaghat earthquake (80^{0}E, 22^{0}N) of 1957 of M=5.5. The seismicity of this region is limited to the shallow crustal depths. The large earthquake happened near the junction of the zone5 and zone 12. For this seismogenic source the mean return period has been estimated as 249 years (also shown by a line on the elapsed time axis), which in turn gives about 64 years and 96 years for the standard deviations assumed as 33% and 50% (please see Table 2) and the cumulative probabilities estimated for these two periods have been found to be nil and 1.4% respectively. The same has been estimated to be about 11% based on the Possoinain distribution. Similar interpretations have been carried out for all the seismogenic source zones and are summarized in Table 2. The table reveals that the cumulative probability for

Table 3. Summary of Conditional probabilities estimated using Weibull distribution for all seismogenic sources for the 15 and 50 years time periods

Source Zones	Year of last occurrence of Earthquake	Return period T_r (Years)	Probabilities using Weibull distribution for different σ and Δt				Poisson, %
			σ_1=0.33T_r		σ_2=0.50T_r		
			15years	*50 years*	*15 years*	*50 years*	
All India	2004	4	100	100	100	100	21
Z_1	1959	192	1	4	3	12	18
Z_2	1940	9	100	100	100	100	100
Z_3	1967	192	24	65	12	36	14
Z_4	1848	339	11	34	7	24	36
Z_5	1997	249	2	6	10	30	10.5
Z_6	1943	57	60	100	42	90	63
Z_7	2003	17	43	100	50	100	10.7
Z_8	1984	44	32	100	32	87	40
Z_9	1958	18	100	100	99	100	96.9
Z_{10}	1997	23	42	100	16	100	27.6
Z_{11}	1989	205	0	0.2	1.0	8.0	9.2
Z_{12}	1990	15	100	100	92	100	66
Z_{14}	1993	40	12	93	94	100	23
Z_{15}	2001	559	6	20	4	14	3
Z_{16}	1999	42	8	82	16	75	13.8
Z_{18}	1999	154	0.5	4.0	2.0	10.00	4.5
Z_{19}	2000	54	4	70	9	54	6
Z_{21}	1720	557	5	20	7	11.5	38.5
Z_{22}	1960	244	0.5	3.0	2.0	9.0	73.8
Z_{23}	2003	10	98	100	89	100	66
Z_{24}	2003	11	90	100	83	100	15.4

Fig. 3 Conditional probabilities for various source zones using Weibull distribution. 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



the 33% T_r have been found to be less than 10% for 15 zones, while it is 100% for zone Z2 and Z9. While the cumulative probability for the 50% T_r is less than 10% for 12 zones, and it is 100% for zone Z2 and Z9. The difference in estimating the cumulative probabilities using 33% and 50% of T_r is less than 5% in 17 cases and is less than 10% for all (with highest as 9.2%). The Poissson distribution is also plotted in the figures for reference only.

The conditional probabilities have been estimated from the cumulative probabilities estimated above for all the seismogenic source zones considering the last occurrence of maximum magnitude in that zone. An example of the same has been given in Fig. 3 for the same zones as shown in Fig. 2. The Poissson distribution is also plotted in the figures for reference only. The conditional probabilities have been estimated for the next 15 and 50 years. The test year 2005 and the return periods are marked on each graph. For example, in case of seismogenic zone 4, where the return period is 339 years, the probabilities for 15 years and 50 years are 11% and 34% for 33% of standard deviation and 7% and 24%

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for 50% of standard deviation respectively. Similarly the conditional probabilities for these two combinations i.e., 15 years and 50 years for two standard deviation values are summarized in Table 3 for magnitude 6.0.

The cumulative probabilities as estimated in Table 2 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 (65.5) 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 seven zones for which the probabilities have been found to be less than 10% while for other ten zones the probabilities were less than 1%. The conditional probabilities were estimated for the two time intervals i.e., 15 and 50 years. The conditional probabilities estimated are given in Table 3. Ten zones namely, Z2, Z6, Z7, Z8, Z9, Z10, Z12, Z14, Z23 and Z24 were found to be having higher probabilities of occurrence of earthquake with maximum observed magnitude in the vicinity of the year 2005.

Results and discussions

The cumulative probabilities as estimated in Table 2 reveals that the zone Z2 (namely Western coast of India extending from Koyna on the south to Ahmedabad) and Z9 (namely Arakan Yoma fold belt) 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 (Andaman Nicobar Islands) and Z12 (Central Himalayan range) where the return period was estimated as 57 and 15 years while the last occurrence was observed in the years 1943 and 1990 respectively. Following the probabilistic hazard computation approach, Khattri *et al*. (1984) published a map in terms of seismic hazard units of g for 10% probability of exceedance in 50 years, calculating the PGA value of the order of 0.7 g for the Himalayan region.

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%. Under the GSHAP (Global Seismic Hazard Assessment Programme), Bhatia *et al*. (1999) came out with a map of the whole of India showing PGA of the order 0.35 g to 0.4 g, based on probabilistic computation approach using Joyner and Boore (1981) attenuation relation. Sharma (2003) has estimated the seismic hazard of Garhwal Himalayan region in north India, and Tyagi (2006) estimated the seismic hazard potential for 50 years based on Artificial Neural Network (ANN) approach. Since these studies considered the probabilistic approach where a combined effect of the seismogenic sources is considered while estimating the strong ground motion, the results obtained in the present study are not directly comparable. Such results can only be compared if the earlier studies had carried out the deaggregation exercise in which the effect of the magnitude and distance is separated and the contribution from the present seismogenic sources is estimated.

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.

The comparison of the Poisonian probabilities with the conditional probabilities using Weibul distribution reveals that the estimates using conditional probabilities are on higher side. The phenomenon may be attributed to the last occurrence of the specific magnitude earthquakes falling inside the return period with a caution that still the cyclic behaviour of seismicity is debatable. The conditional probabilities using Weibul distribution are on higher side after crossing the return period since the Poisonian distribution is independent of the elapsed time. It may be concluded that the unnecessary loading of the seismic hazard in terms of higher recurrence periods should be avoided and the conditional probabilities for estimation of recurrence periods should be used which takes into consideration the occurrence of the last earthquake of specific magnitude. The analysis emphasizes 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. Most often the uncertainties are explicitly associated with the parameters like the return period, which in turn are estimated from the frequency magnitude distributions. A complete earthquake catalogue is required for such studies for better estimation of a, b, T_r and its variability for realistic computation of recurrence periods of seismic events.

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