Probabilistic Assessment of Earthquake Hazards in the Indian Subcontinent

Abstract

A problem of increasing concern of the likelihood of occurrence of the next large earthquake in the seismically active regions in India where the last occurrence has crossed the return periods, the conditional probabilities have been estimated using Weibull,Gaussian,Lognormal and Poissonian distribution for the Indian region. The estimations have been carried out by dividing the Indian subcontinent into 24 seismogenic sources. The cumulative and conditional probabilities have been interpreted with respect to the last earthquake occurrence and in the time intervals of 15 and 50 years. The results are discussed by comparing the estimated cumulative and conditional probabilities estimated for each zone. The use of conditional probabilities have been recommended for estimation of seismic hazard to take into account the last occurrence of earthquake in the region.

Keywords: Seismic Hazard, Probabilistic Distribution, Cumulative Probability and Conditional Probability

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Introduction

An earthquake is a very complex phenomenon; it can cause buildings and bridges to collapse, disrupt lifelines such as water, gas, electricity, roads and network service, and often trigger landslides, fires, and tsunamis. Earthquakes are still difficult to predict as to when it will happen. Therefore, one should be well prepared for minimizing the damage caused by an unexpected earthquake in all conceivable ways.

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. Seismic hazard, generally, is defined as the probable level of exceedance of ground shaking associated with the recurrence of earthquakes. The seismic hazard estimates, generally, 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 (Sharma, 2003, Ameer, 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 conditional probability of occurrence. It is also necessary to know the frequency distribution of recurrence intervals of a given magnitude or magnitude range.

Seismotectonics of Indian Region

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. These source zones were chosen on the basis of Khattri et al. (1984) work in which the whole Indian region is divided into 24 independent seismogenic source zones. The division into the source zones is based on the geological and tectonic setup of the area, past seismicity and other geophysical anomalies considered by Khattri et al (1984).. Figure 1 shows the source zones considered in the study for seismic hazard assessment.. 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.

The source zones have been divided based on Khattri et al. (1984).

Zone 1

This zone consists of eastern coastal belt includes part of Mahanadi and Godavari garbens. The major part of the zone comprises of Archean rocks and Precambrian fault systems. The general tectonic trend in this zone is in an ENE 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).

Zone 2

Western coast of India extending from Koyna on the south to Ahmedabad on the north has occasionally had 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). On the north, a north-northwest-trending graben is filled with thick tertiary sediments and tertiary and quaternary synsedimentary faulting. A major tectonic feature of lower Miocene age called the Panvel flexure runs in a northerly direction extending from latitudes 16^oN to 21^oN.

Zone 3

Kutch region is a major zone of shallow-focus seismic activity, second in activity only to the active plate boundary zones.. A severe earthquake (Io=XI) that occurred in 1819 was accompanied by the formation of the ridge near Lakhpat (68.7^oE, 23.7^oN) in an easterly direction. The ridge was 24 km wide and 10 km long with elevation changes of several meters (Oldham, 1883). Another significant earthquake occurred at Anjar (70.0^oE, 23.0^oN) in 1956, with m=6.1 and I_o=IX.

Zone 4

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 (72.4^0E, 24.8^0N) in 1969.

Zone 5

This zone covers the Narmada –Tapi rift, a system of deep seated fault of region al significance (Naqvi et al., 1974). The other significant earthquakes noticed in this zone are Son Valley earthquake (81.0^0E, 23.5^0N) of 1927 (M=6.5), Satpura earthquake (75.7^0E, 21.5^0N) of 1938 of M=6.3 and the Balaghat earthquake (80^0E, 22^0N) of 1957 of M=5.5.

Zone 6, 7, 8

The Andaman-Nicobar Islands were formed by the convergence of the Burmese and Indian crustal plates, resulting into an anticlinical belt with faults parallel to the island structure.. The seismicity of this Island arc system has been broken into three zones zone 6, zone 7, and zone 8. Zone 6 indicates the outer margin of seismic belt, which constitutes of only shallow focus events. This area has experienced several major earthquakes. In zone 7 one great earthquake of 1941 of M=8.7 thirteen shallow earthquake and eight deep earthquake with magnitude in the range 7-8 have been reported. In comparison to zone 7, in zone 6 only three major shallow earthquakes in the range 7-8 have been noticed, of which the largest was of M=7.7. In zone 8, the largest reported earthquake was of magnitude 6.7.

Zone 9

This zone 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). The highly folded allocthonous zone is the northerly-trending geological province it is continuation into the continent of the Sumatra, Andaman, Nicobar, Java island arc system faced by the thurst zones and other fault, which is formed by the Indian and Burmese plates (Deshikacher, 1974; Verma et al., 1976).

Zone 10

The Bramhaputra valley forms one of the most seismically active areas in the subcontinent. North of the Bramhaputra valley is covered by the frontal Himalayan ranges and southeast of it by the schuppen belt of Naga Hills and Arakan Yoma ranges. To the east, the characterization of the lower side of Brahmaputra valley is done by recent alluvial cover that conceals considerable thickness of the tertiary segments.

Zone 11

This zone constitutes of 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 directions with a hinge zone passing close to the Calcutta (Sengupta, 1966). This area seems to had 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). A destructive earthquake of magnitude 5.7 occurred in the area in 1969.

Zone 12&14

Zone 12 and 14 covers the Himalayan tectonic unit, which constitutes the world’s highest mountain chain. In the interior of the Himalaya an orogenic zone is leaded by number of east trending thrusts (Gansser, 1964; Valdiya, 1973; Lefort, 1975; Geological survey of India, 1979). The seismicity of this area is broken into two narrow zones, zone 12 and 14. Zone 12 covers the central Himalaya range, which is close to the Main Central Thrust which is the main locale of seismicity. The seismicity of this zone is low. 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. Occurrence of large earthquakes near the junction of tectonic linements should be considered while estimating seismic hazard in these localities (Gorshkov, 1974).

Zone 15

This 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, 19

These three zones cover the entire length of Kirthar-Sulaiman mountain ranges in the northwest part of the Indian subcontinent. This region has been divided into three source zones according to the intensity of the seismicity in the past years. These ranges constitute of number of Tertiary and Mesozoic arcurate faults and imbricated structures (Krishnan, 1968), which includes Chaman fault, which is a major fault system that is active along its whole length, extending in a general north-northeast direction. 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

This zone is consisting 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.

Zone 20, 21, 22

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.. According to the past records these zones seems to have had low seismicity. The largest reported earthquake in the past year having a magnitude about 6. Similarly zone 20 also have low- magnitude seismicity and is concerned with Northeast trending faults in the basement.. It is believed that such area is prone to large earthquakes of active tectonics (Gorshkov, 1974), such zones used to have considerable seismic potential.

Zone 23

It 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. It is a seismically active zone.

Zone 24

The Pamir knot. This area 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.

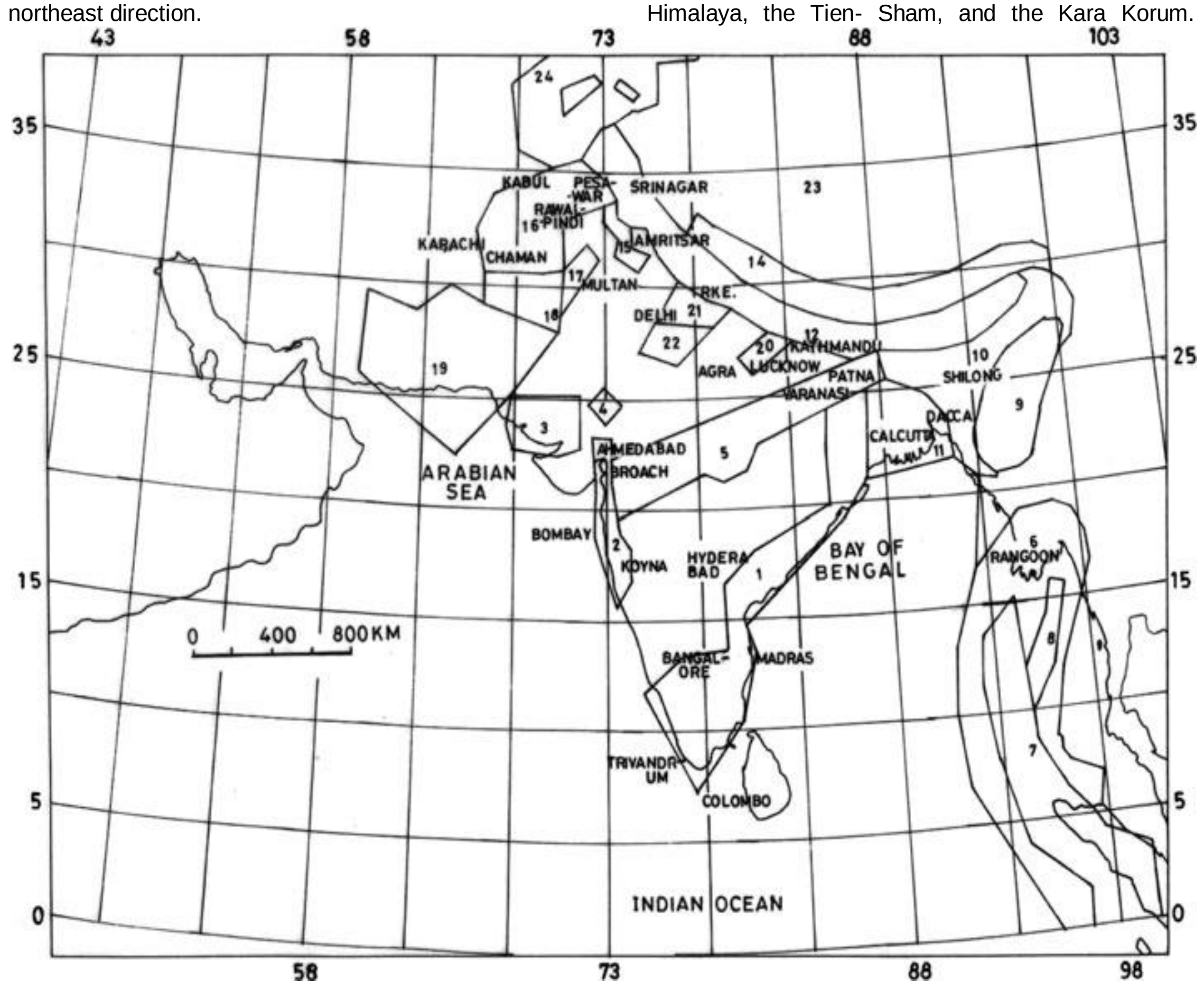

Figure 1 Seismogenic sources in India (after Khattri et al. 1984)

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 (1975), and a thorough statistical discussion is in Vere-Jones (1970). Hagiwara (1974) and Rakitake (1975) 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≥6.0 and M≥5.0) in a specified interval of time for different elapsed times on the basis of observed time-intervals between the large earthquakes (M≥6.0 and M≥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 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

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

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]:

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

$$\frac{\sigma}{T_r} = \left[\Gamma\left(\frac{v+2}{v}\right) - \Gamma^2\left(\frac{v+1}{v}\right)\right]^{1/2} / \Gamma\left(\frac{v+1}{v}\right) \quad (2)$$

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:

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

which yields a conditional Weibull probability of

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

Gaussian Distribution

The Gaussian distribution has been used by a number of authors to estimate conditional probabilities of seismic zones in Japan and the United States (Wesnousky et al., 1984; Sykes and Nishenko, 1984; Jacob, 1984, Johnston and Nava, 1985). In the present case the past seismicity data has been used by considering the Gutenberg Richter distribution (Gutenberg and Richter, 1954) for estimating the mean recurrence periods for various magnitudes. The Gaussian (or normal) probability density function is given by

$$g(t) = \frac{1}{\sigma (2\pi)^{1/2}} \exp\left[-\frac{1}{2}\left(\frac{t - T_r}{\sigma}\right)^2\right] \quad (5)$$

where σ is the standard deviation and Tr is the mean repeat or recurrence time: The cumulative probability may be given by $G(T \le t) = \int_{-\infty}^{t} g(\tau)\,d\tau$. This integral cannot be evaluated by standard techniques, but extensive tables of values are available when G(T ≤ t) is transformed into a standardized normal distribution by using $z = \frac{t - T_r}{\sigma}$. The Gaussian conditional probability may be given by

$$G_c(t, \Delta t) \rightarrow G_c(z, \Delta z) = \frac{G(z+\Delta z) - G(z)}{1 - G(z)} \quad (6)$$

Where the values for G (z+Δz) and G (z) may be taken from standard tables.

Lognormal Distribution

The lognormal distribution can be generated from the Gaussian (or vice versa by the variable transform t= ln (t), where ln is the natural (base e) logarithm. A lognormal density function l(z) is obtained from the standardized normal distribution using the following relations:

$$z = \frac{In(t) - T^{*}_{r}}{\sigma^{*}} \quad \sigma^{*} = \left[In\left(\frac{\sigma^2 + T^2_{r}}{T_r^{\,2}}\right)\right]$$

$$T^{*}_{r} = In(T_r) - \frac{\sigma^{*2}}{2} \quad (7)$$

where T^{*}_{r} and σ^{*} are the mean and standard deviation of the lognormal distribution. The lognormal distribution has found frequent application in the earth sciences [e.g., Till, 1974] and in at least one case has been applied to earthquake recurrence times. Jacob [1984] compared the fit of the intercurrence intervals of large (Ms ≥ 7.8).

Poisson Distribution

Poisson statistics have been used extensively to represent time sequences of earthquakes. In many cases, seismic zones seem to emulate closely a Poisson process. However, this is a different property from the one of interest here, which is the distribution of occurrence times about an average recurrence time for a given magnitude range. For this, Poisson probabilities are not an adequate representation because the independence of Poisson events results in a constant conditional probability rather than on increasing in time since the last event as required by the time-predictable model.

More useful for our purposes is the distribution of inter event times which may be shown to follow a negative exponential distribution for a Poisson process [Lomnitz, 1974]:

$$s(t) = \frac{1}{T_i} e^{-t/T_i} \qquad (8)$$

where T_i is the average inter event time (Johnston,1985).

The cumulative Poisson probability for a time interval T ≤ t and for an average recurrence time T_r is

$$S(t \le t) \int_0^t s(\tau)\, d\tau = 1 - e^{-1/T_r} \qquad (9)$$

conditional probability

$$S_c(t, \Delta t) = 1 - e^{-\Delta t/T_r} \qquad (10)$$

Where Δt is the time interval under consideration for an earthquake reoccurrence. Note that for a given Δt, S_c is constant and does not depend on t, the elapsed time since the last event.

Estimation of Cumulative and Conditional Probabilities for Indian Region

Magnitude

Most of the seismic hazard studies have reported the return periods for the magnitude 6.0 and for other magnitude ranges the probabilities are estimated using the distributions assumed for its recurrence. Therefore, we restrict our data presentation to magnitude 6.0.

Average recurrence interval

In the absence of any geological or paleoseismological information this parameter is taken directly from the frequency-magnitude analysis

Standard Deviation

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. The standard deviation σ is allowed to vary from one third (33%) to two thirds (67%) of T_r. For σ in excess of $0.5T_r$ the very concept of the time-predictable seismicity model loses much of its meaning.

Time interval Δt

We selected a Δt of 15 years to estimate it for 2020 and a Δt of 50 years as representative of the probability of occurrence during a lifetime of any engineering structure.

In Figure cumulative probabilities are shown for mb ≥6.0 earthquake with a mean recurrence interval form the extreme upper end of its range and year of last earthquake. Poisson values are significantly higher than the other distributions for t < T_r and lower for t > T_r.

Conditional Probability

Conditional probabilities for seismogenic sources earthquakes for the next 15 and the next 50 years are presented.. The data are presented in each depicting conditional probabilities Pc for Gaussian, Weibull, lognormal, and Poisson distributions. The plots have been carried out to elapsed time double or triple Tr so that asymptotic behavior of Pc at large t would be shown. Three reference times, to, Tr, and t = year of last earthquake, are shown on each graph.

Results and Discussions

The fitting of GR relationship to the individual zones show that the return period of magnitude 6.0 varies form 4 years to 559 years. The minimum return period is for all Indian zone where a magnitude is reported anywhere in Indian region with in 4 years which matches well with the occurrence of moderate earthquakes in the last two decades The largest return period is computed for the source zone 15 which 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.

For the all India zone the extreme value estimated is about 7% for the cumulative probability. This is estimated in 2005 and the last earthquake has happened in 2004 with return period as 4 years. The zone 1 shows very little cumulative probability i.e., 5.4% since the return period is 192 years and the last earthquake has happened in 1959. The area has experienced an occasional earthquake of magnitude 5-6, with the largest reported magnitude of 6.

The source zone 2 has shown the cumulative probability to be 100% since the return period estimated is 9 years while the last earthquake reported was in 1940 where the seismicity is confined to shallow crustal depths Kumar et al (2006).

The lower bound of the cumulative probability estimation is 0% in case of 16 zones where the Tr. is still not crossed by the present year of estimation i.e., 2005. The upper value in the extreme cumulative probabilities shows values less than 1% in case of Zone 11 and 15 while it is 1.5 in case of zone 24. The zones having cumulative probabilities between 1 and 10 % are zone all Indian, 1, 3, 5, 7, 10, 16 and 24. The zones having cumulative probability between 10 and 50% are zone 6, 14 and 21. While the zone 6 and 12 has the cumulative probabilities between 50% and 80%. The zones having cumulative probabilities between 80% and 99% are zone 4 and 22.

The future probabilities in terms of conditional probabilities for the two time intervals viz., 15 and 50 years are calculated. For the All India Zone the extreme ranges are 100% due to its lower return period which is only 4 years. While the 15 years will give the 2020 year as the computational year, the 50 year time interval is chosen because of the life time period of most of the engineering and non engineering structures. There are 13 zones which shows their extreme values to touch 100%. It was observed that allowing σ to range from 0.33 Tr to 0.50 Tr has a greater effect on conditional than on cumulative probability but only for t > Tr times generally beyond our concern in this study. For times less than roughly one-half Tr an increase in σ increases Pc because area beneath the probability density function is shifted from the distribution mean Tr to the distribution tails. However, for t ≥ Tr, Pc for σ = 0.50 Tr is always less than Pc for σ = 0.33 Tr. The constant Poisson conditional probabilities will yield estimates that are consistent with the other distributions only over a vary restricted range of elapsed times and should not be used for conditional probability estimation for a time predictable model of seismicity. In contrast, Poisson cumulative probabilities are consistently high for t < Tr and may be used to provide a conservative (i.e., upper bound) estimate of seismic hazard.).

The probability estimates of this report rely on the assumption that the Indian seismic zone generates major earthquakes in a repeated fashion. It is further assumed that the occurrence of large events is periodic rather than episodic, a distinction we make on the basis of the standard deviation of repeat times about the mean recurrence interval. If σ is less than 50%, the calculated probabilities reported here should be reasonable estimates of the likelihood of future Indian earthquakes.

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