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# Estimation of Probabilities of Occurrence of Moderate Earthquakes using Lognormal Model in Indian Region

**Abstract**

The present paper presents conditional probabilities of recurrence of moderate in the seismically active regions in India. 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 Lognormal distribution. For this purpose, the Indian subcontinent have been divided into 24 seismogenic sources. It is estimated through cumulative probability 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.

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**Keywords:** Conditional Probabilities, Lognormal, Seismic Hazard, Seismic Zones, Earthquake Recurrence.

**Introduction**

Over the past decades considerable effort has been focused on obtaining realistic assessments of seismic hazards (Kiremidjian and Shah, 1975; Mortgat and Shah, 1979; McCann, 1981; Shah and Dong, 1984; Wesnousky, 1986; Lamarre and Shah, 1988). 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. As the understanding of the earthquake generating mechanism and of the seismic wave propagation pattern improve, the models to describe earthquake recurrence and magnitude distribution become extremely complex and require substantial data for parameter estimation. The purpose of the present study to estimate the conditional probabilities of occurrence of earthquakes based on lognormal distribution.

**Objective of the Study**

The main objective of this research paper is to assess the seismic hazard for the Indian region. The seismotectonics modeling was carried out to define and delineate the seismogenic sources for seismic hazard assessment for individual seosmogenic source zones. Lognormal distribution was applied to estimate the seismic hazard. The cumulative and the conditional probabilities estimated by considering the return period and the last occurrence of the earthquake due to the source in the recent past.

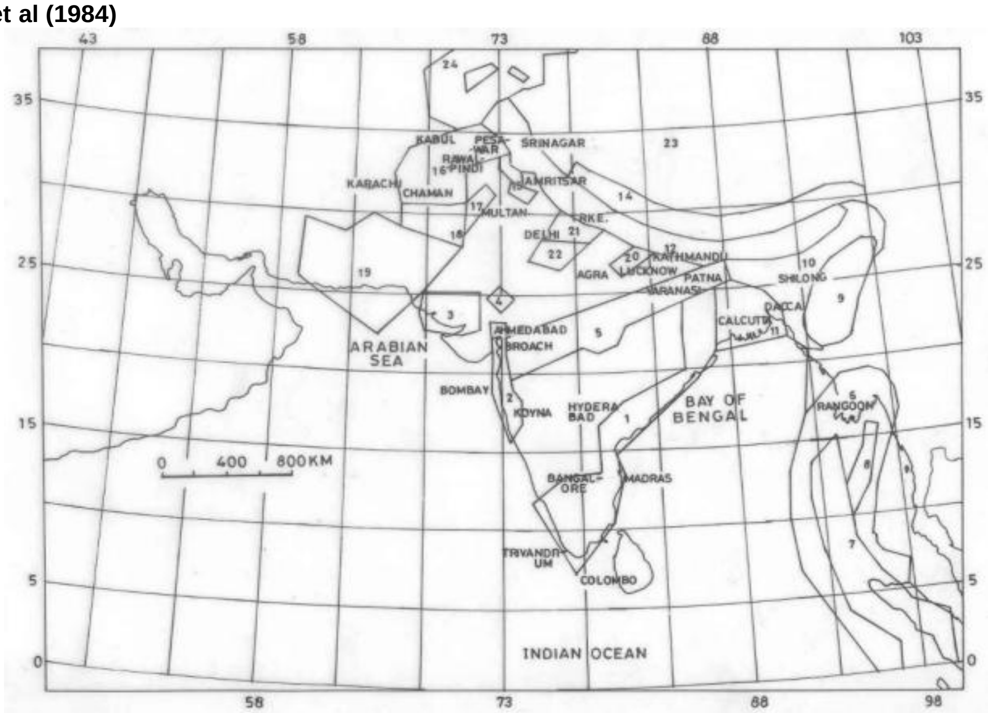
**Review of Literature**

From the beginning of the $20^{th}$ century, more than 700 earthquakes of magnitude 5 or more have been recorded and felt in India, as presented in the catalogues prepared using information collected from United State Geological Survey (USGS), India Meteorological Department, National Geophysical Research Institute, International Seismological Commission (ISC) and other published work. To explain the cause of occurrence of earthquakes and to understand the seismotectonics of the Himalayan collision zone, various models have been proposed for the evolution of the Himalaya. The evolutionary model (Ni and Barazangi, 1984) postulates that zone of plate convergence is progressively shifted south by formation of intracrustal thrusts. Himalayan zone is divided into two phases. The first phase consist of continent-continent collision of India and Asia and the second phase involved the stretched Indian continental lithosphere subducted along the detachment surface forming intra-continental thrusts (Powell and Conaghan, 1973; Ni and Barazangi, 1984). Various time-dependant seismic renewal models came into existence of which gamma, lognormal and weibull distribution became the leading ones (Utsu, 1984; Parbez and Ram 1999; Tripathi, 2006; Yadav et al. 2008, 2010; Pasari and Dikshit, 2015, 2018).

**Seismicity Pattern and Zonation of the Indian Subcontinent**

Tectonic framework of the Indian subcontinent covering an area of about 3.2 million sq. km is spatio-temporally varied and complex. The study area has been divided into 24 independent seismogenic source zones having individual characteristics (Khatri et al., 1984; Figure 1) for seismic hazard assessment. The zone I includes part of Mahanadi and Godavari graben mainly comprises of Archean rocks and Precambrian fault systems. 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)**



**Probabilistic Model and Their Parameters**

A number of researchers have carried out statistical studies of the recurrence interval for the great earthquakes which mostly occurred along the plate boundaries and at a number of subduction zones (Hagiwara, 1974; Rikitake, 1976, 1991; Nishenko and Buland, 1987; Papazachos and Papaioannou, 1993; Parvez and Ram, 1997). In the present study, the intention has been to analyse the recurrence intervals of the earthquakes using lognormal model given by UTSU (1984). The details of the Lognormal model have been briefly described below.

**Lognormal Distribution**

The lognormal distribution occurs in practice when we encounter a random variable, which is such that its logarithm has a normal distribution. In earth sciences it has frequent applications. [Till, 1974]. It has also been applied to earthquake recurrence times. Jacob (1984) compared the fit of the interoccurrence intervals of Aleutian earth quakes of large magnitude (m > 7.8) to both Gaussian and log normal distribution and considered the log normal to be the more appropriate representation. 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:

$$z = \frac{In(t) - T^{*}{}_{r}}{\sigma^{*}} \quad \sigma^{*} = \left[ In\left( \frac{\sigma^{2} + T^{2}{}_{r}}{T_{r}^{\,2}} \right) \right] \qquad (1)$$

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

Where $T^{*}_{r}$ and $\sigma^{*}$ 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.

**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. In the present study the standard deviation $\sigma$ is allowed to vary from one third (33%) to two thirds (50 %) of $T_r$ (Kumar, 2006). The observed variability of the repeat times of magnitude 5 and 6 earthquakes in the historical record [Nuttle and Brill, 1981] suggests that $\sigma$ should not be smaller than one third of $T_r$. In Figure 2, for the source zones Z4, Z5, Z7, Z19, Z21 and Z24 cumulative probabilities for lognormal model are shown for $m_b \geq$ 6.0 earthquake with a mean recurrence interval form the extreme upper end of its range and year of last earthquake are listed in Table 1. The conditional probability estimation for these source zones are shown as an example in Fig. 3.

**Table 1 : Summary of Cumulative probabilities : 2005**

| Source Zones | Year of last Earthquake | $T_r$ (Years) | $\sigma_1$ = o.33$T_r$ | $\sigma_2$ = 0.50 $T_r$ | Lognormal, % | |
|---|---|---|---|---|---|---|
| | | | | | $\sigma_1$ | $\sigma_2$ |
| **All India** | **2004** | 4 | 1.32 | 2 | 0 | 4.0 |
| **$Z_1$** | 1959 | 192 | 63.36 | 96 | 0 | .2 |
| **$Z_2$** | 1940 | 9 | 2.97 | 4.5 | 100 | 100 |
| **$Z_3$** | 1967 | 192 | 63.36 | 96 | 0 | .2 |
| **$Z_4$** | 1848 | 339 | 111.87 | 169.5 | 3 | 82.5 |
| **$Z_5$** | 1997 | 249 | 82.17 | 124.5 | 0 | 0 |
| **$Z_6$** | 1943 | 57 | 18.8 | 28.5 | 70 | 68.5 |
| **$Z_7$** | 2003 | 17 | 5.6 | 8.5 | 0 | 0 |
| **$Z_8$** | 1984 | 44 | 14.5 | 22 | 0 | 0 |
| **$Z_9$** | 1958 | 18 | 5.9 | 9 | 100 | 99 |
| **$Z_{10}$** | 1997 | 23 | 7.59 | 11.5 | 0 | 1.5 |
| **$Z_{11}$** | 1989 | 205 | 67.65 | 102.5 | 0 | 0 |
| **$Z_{12}$** | 1990 | 15 | 4.95 | 7.5 | 58.5 | 47.6 |
| **$Z_{14}$** | 1993 | 40 | 13.2 | 20 | 0 | 0 |
| **$Z_{15}$** | 2001 | 559 | 184.47 | 279.5 | 0 | 0 |
| **$Z_{16}$** | 1999 | 42 | 13.86 | 21 | 0 | 0 |
| **$Z_{17}$** | - | - | - | - | - | - |
| **$Z_{18}$** | 1999 | 154 | 50.82 | 77 | 0 | 0 |
| **$Z_{19}$** | 2000 | 54 | 17.82 | 27 | 0 | 0 |
| **$Z_{20}$** | - | - | - | - | - | - |
| **$Z_{21}$** | 1720 | 557 | 183.8 | 278.5 | 3 | 18.5 |
| **$Z_{22}$** | 1960 | 244 | 80.5 | 122 | 0 | 0 |
| **$Z_{23}$** | 2003 | 10 | 3.3 | 5 | 0 | 0 |
| **$Z_{24}$** | 2003 | 11 | 3.6 | 5.5 | 0 | 0 |

**Fig. 2 : Cumulative probabilities for lognormal model for $m_b \geq 6.0$ earthquake.**

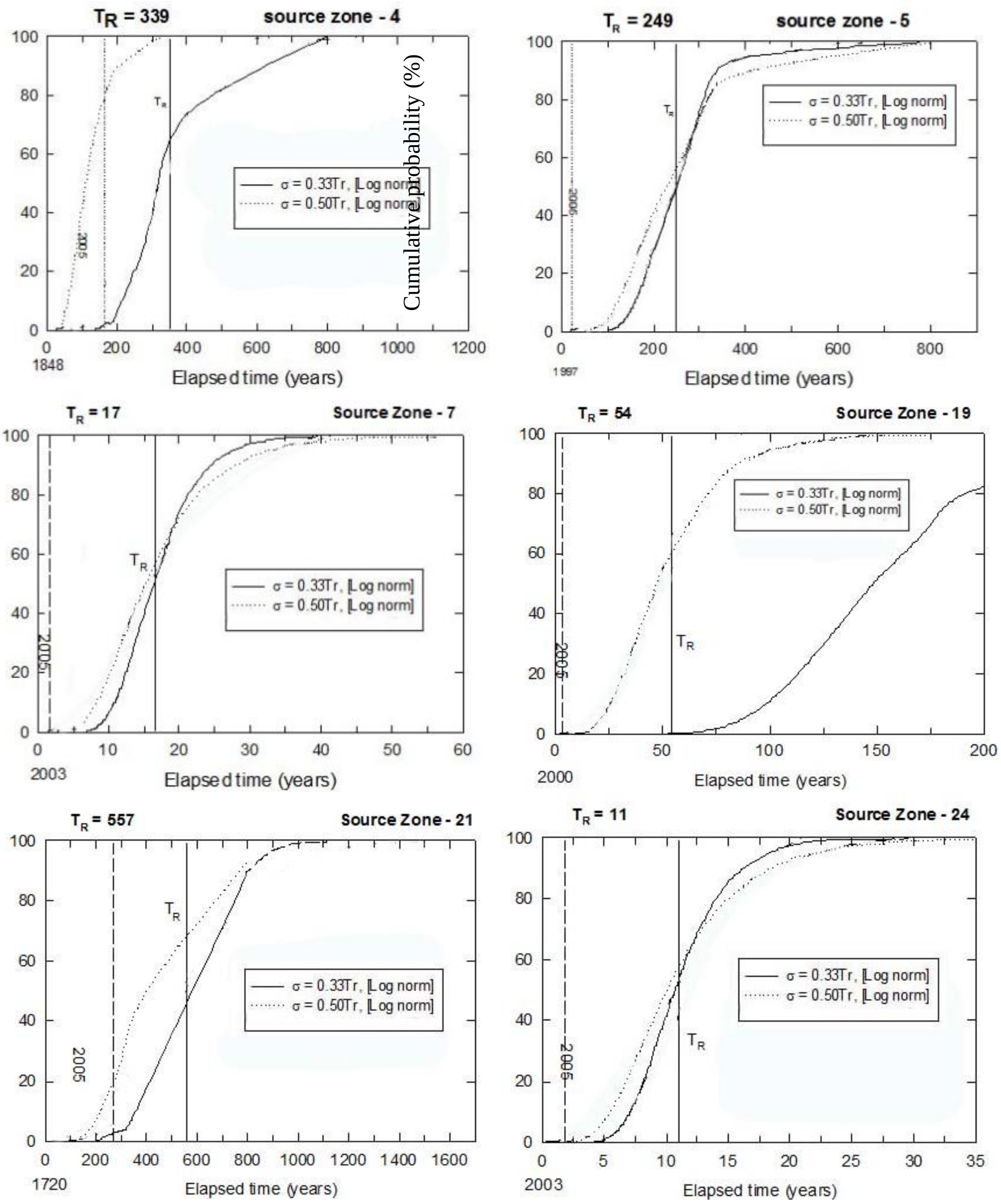
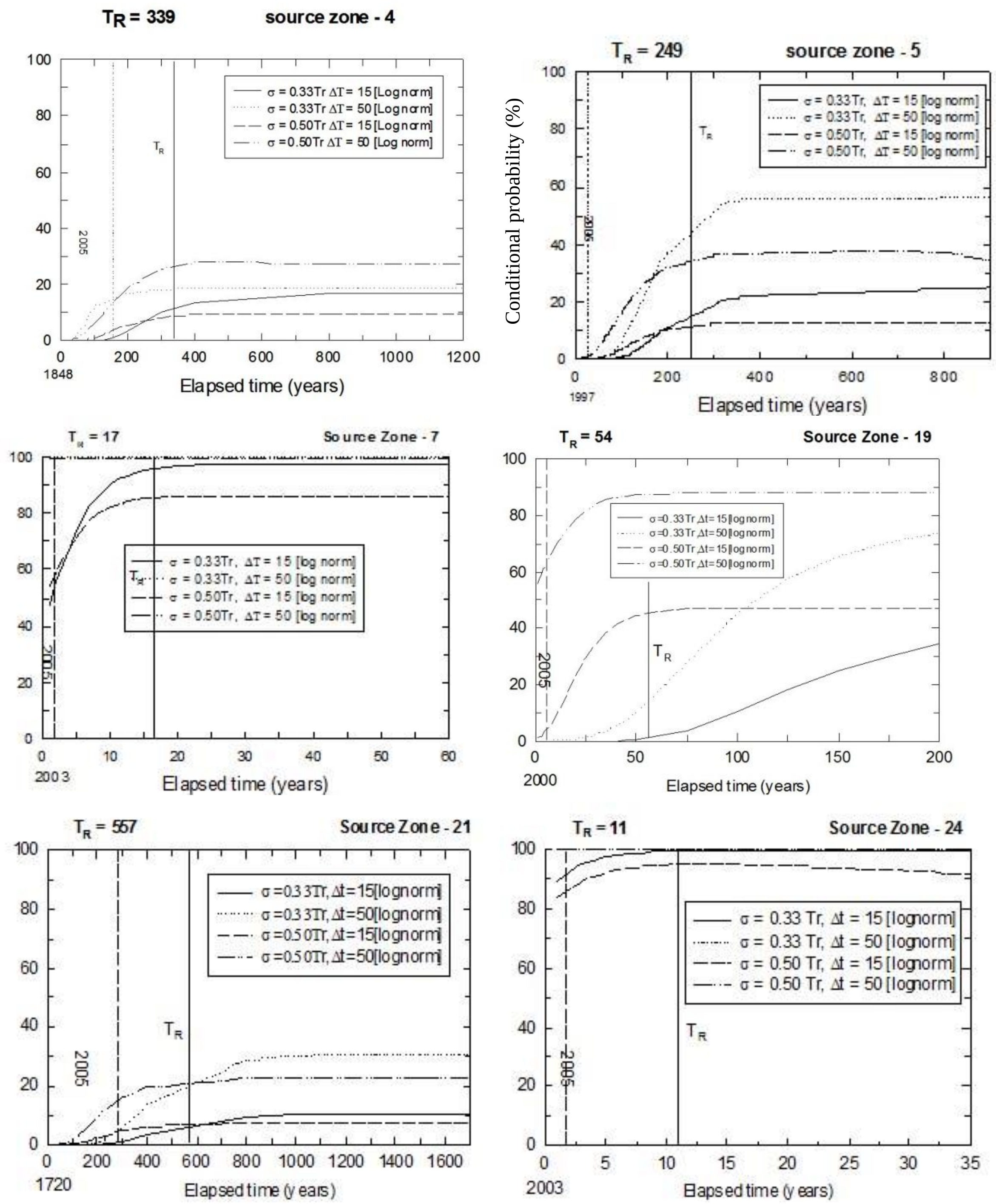


**Fig. 3 : Conditional probabilities for lognormal model for selected six zones.**




**Discussion and Conclusion**

The time recurrence models of extreme value distribution are valid, as various researchers have found it. The results obtained in the present investigations also favour the validity of the lognormal model in 24 seismogenic zones in Indian regions. The seismic hazards for the Indian subcontinent were studied by a number of researchers (e.g., Auden, 1959; Gaur and Chouhan, 1968; Kaila et al., 1972; Kaila and Rao, 1979; Khattri et al., 1984; Khattri, 1992; Parvez and Ram, 1997). Khattri et al. (1984) have produced the probabilistic seismic hazard map showing peak ground acceleration for the Indian and neighbouring areas. The cumulative probabilities as estimated in Table 1 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. 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. For the earthquakes $M\geq6.0$, the estimated cumulative probability reaches 0.9 after about 53, 54 and 55 years for Lognormal model (Tripathi, 2006). 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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